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INTERFERENCE PROTECTION REQUIREMENTS FOR TERRESTRIAL MICROWAVE LINKS IN THE UK PRIVATE-USER FREQUENCY BANDS

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Summary

Many broadcast television circuits are carried on microwave links in the private-user frequency bands. At present the television signals are carried in analogue form. High data-capacity links would be required to allow television signals to be carried in digital form. The bandwidth available in the lower frequency private-user bands (which are more desirable as they allow longer hop lengths) is limited. As a result, more sophisticated, bandwidth-efficient modulation techniques are required.

Systems using more than four amplitude and phase states are not currently used in the private-user frequency bands. Before they can be introduced the protection requirements for interference to and from each of the many different analogue and digital systems used at present in these bands must be determined. This Report describes a set of experimental measurements and theoretical calculations to determine the interference protection requirements of dissimilar analogue and digital systems.

Recommendations are made as to the most suitable method of determining the protection ratios required for interference between systems. This approach should be used to determine the protection requirements, both for new systems and existing ones. It is also recommended that the receive filter response should be specified and checked during type-approval tests and that the transmit spectrum masks should be modified to reduce the permitted level of out-of-band radiation.

Index terms: *ACI; BER; CCI; FM; frequency allocation; frequency assignment; PSK; RF; SHF; TV links*

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1. INTRODUCTION

Many broadcast television circuits are carried on microwave fixed radio-links in private-user bands. Analogue equipment has been extensively used in the past, however it is likely that the emerging technology of digital coding of television for transmission will force these circuits to be replaced by digital links. For many other users, this natural transition from analogue to digital systems is already well advanced, as they are replacing their worn-out, low and medium capacity telephony systems.

Even using state-of-the-art coding techniques, medium data-capacity circuits would only carry one video circuit at a time, which is not sufficient for many broadcasting purposes. High data-capacity circuits would be more appropriate as they give some flexibility in the choice of coding and the number of circuits carried. At the moment, because of bandwidth limitations, high capacity circuits can only be allocated in the 22 GHz private-user band. Rain attenuation at these frequencies limits their use to hops of less than 15 km — which is too short for most television signal links.

Most existing BBC links have assignments in the 7.5 GHz band, and many are operated successfully with hop lengths in excess of 50 km. It is likely that digital replacements would achieve similar performance over these sorts of distances provided that they can also use the 7.5 GHz band. For shorter links of less than 40 km the higher frequency bands of 13/14 GHz would be suitable.

For the BBC to make use of radio links for television in digital form, the provision for high-capacity digital circuits needs to be extended to the lower frequency bands. Such a proposal has been made to the Radiocommunications Agency (RA), formerly Radiocommunications Division of the Department of Trade and Industry, which is responsible for licensing of the private-user bands. The RA's view is that any new requirement such as this should be compatible with the existing channel allocations. This implies that the proposed high data-capacity systems would need to use bandwidth-efficient modulation techniques so that they can fit into an RF channel intended for medium capacity use. Such modulation systems are not currently used in the private-user bands.

Before these more sophisticated digital radio links could be introduced, the RA's frequency planners need to know how vulnerable existing services are to interference from the new systems. Similarly, they also need to know the degree of protection required from interference caused by the wide range of existing services. As these figures were not available, a set of tests was conducted to determine them. This Report presents the results of these tests, which are an essential precursor to further progress of the BBC's proposal to introduce the use of high capacity links in the lower frequency private-user bands.

Minimum requirements for interference protection have been determined by means of both practical measurements on typical link equipment, and also by calculated predictions. This Report brings together the results of these two separate approaches to the problem for comparison, and makes recommendations as to how they could be best used for frequency assignment purposes.

2. BACKGROUND

The Telecommunications Act 1984, which is subject to review from January 1991, makes provision for private users to operate microwave fixed links in the UK in one of two ways. Firstly, under strictly limited circumstances, a licence to operate the link can be obtained. Secondly, if the intended use of the link satisfies a number of specific conditions, then it is exempt from licensing.

The majority of today's private-user links are those exempt from such licensing. This is because current government policy is that all proposed links, which do not satisfy the conditions for exemption, should be provided by one of the Public Telecommunications Operators (PTOs) such as: British Telecom, Mercury Communications or Kingston Communications. The Office of Telecommunications (OFTEL) is consulted for advice on whether a licence is required.

In addition to meeting the requirements of the Telecommunications Act 1984, which regulates the operators of fixed links, all links must have a Wireless Telegraphy Act 1949 licence. This licence is the mechanism by which technical standards are controlled so that frequency bands can be shared between all users. It is the responsibility of Fixed Services Section of the RA to assign frequencies and issue the Wireless Telegraphy Act licence for new links.

Private-user bands are expected to cater for a wide variety of traffic ranging from simple low-capacity telemetry, to 480-channel digitally-coded telephony, and broadcast-quality television (medium capacity). At the moment, there is little or no use of high-capacity (1,920 telephony channels) circuits. As the RA aims to make the best possible use of the limited spectrum available, it will assign the minimum RF channel bandwidth necessary for the traffic required. This means that each band contains a mixture of channel bandwidths. The situation is further complicated by the use of both analogue and digital modulation systems.

Further economy in the use of the available bandwidth is achieved by planning for the maximum possible re-use of frequencies without causing undue interference. This can only be successful if all links are engineered to achieve, at least, a minimum standard of performance. For this reason, link transmitters, receivers and antennas must all conform to specifications published by the RA before a licence is issued for the link. Conformity is on the basis of 'type approval' rather than individual acceptance tests. These type-approval tests check the performance of a sample of equipment produced by manufacturers. The checks made depend on what the equipment is (for example, a transmitter, a receiver, etc.). For the purposes of this Report, it is important to know that a transmit spectrum shape, and levels of out-of-band spurious signals are both specified and these levels must not be exceeded. The transmit spectrum shape is known as the 'spectrum mask' and is discussed further in the Report.

Another vital component in the process of frequency planning is the knowledge of how the different systems are affected by co-channel and adjacent-channel interference. As might be expected, the planning criteria for interference between like systems are generally well known and come from considerable world-wide PTO experience. Unfortunately, there is much less known about the interaction between the diverse range of systems encountered in the private-user bands.

In 1984 a series of trials was carried out at the RA's Kenley laboratories to determine the compatibility of low and medium capacity digital radio equipment with existing analogue systems. The outcome of these trials was the successful introduction of digital radio systems into private-user bands. The results obtained were used in conjunction with theoretical calculations to produce the current planning criteria for frequency assignment.

A number of frequency bands are available for private-user links; these are shown in Table 1.

Table 1
Frequency Bands available for private-user links

Band	Circuit capacity	Typical max hop length
1.5 GHz	Low	>50 km
7.5 GHz	Medium	<50 km
13 GHz	Low/Medium	<40 km
14 GHz	Low/Medium	<40 km
22 GHz	Low/Medium/High	<15 km

A series of specifications is published, as the equipment performance required in each band is different. For example, frequency assignments are usually internationally co-ordinated to CCIR recommendations and different arrangements apply in each band. Other considerations such as equipment cost, propagation characteristics and the limitations of current technology need to be taken into account. In producing the specifications, the RA consults with the manufacturers and users of private fixed links. The forum for this discussion is the Microwave Fixed Link Specification Committee (MFLSC).

The MFLSC is made up of representatives from the RA, UK manufacturing industry, the PTOs and all private users (such as public utilities, the off-shore oil industry, and broadcasters). Active participation in putting together a new specification or modifying existing ones takes place in sub-groups set up by the MFLSC. The work reported here was performed to provide a contribution to the Digital Working Group of the MFLSC in support of a proposal to admit high data-capacity systems into the 7.5 GHz, 13 GHz and 14 GHz bands.

3. BASIC LINK CONSIDERATIONS

This section is a general introduction to some of the basic characteristics of digital terrestrial microwave links. It will focus on those aspects which explain the choice of the performance criteria used for assessing interference from other link systems. It is not essential reading for those readers who are already familiar with digital links and their failure mechanisms.

The simplified representation of a digital link, Fig. 1, identifies the basic functional elements of typical link terminals. The primary impairments that the equipment designer and the systems engineer need to overcome are equipment imperfections, noise, interference and multipath propagation.

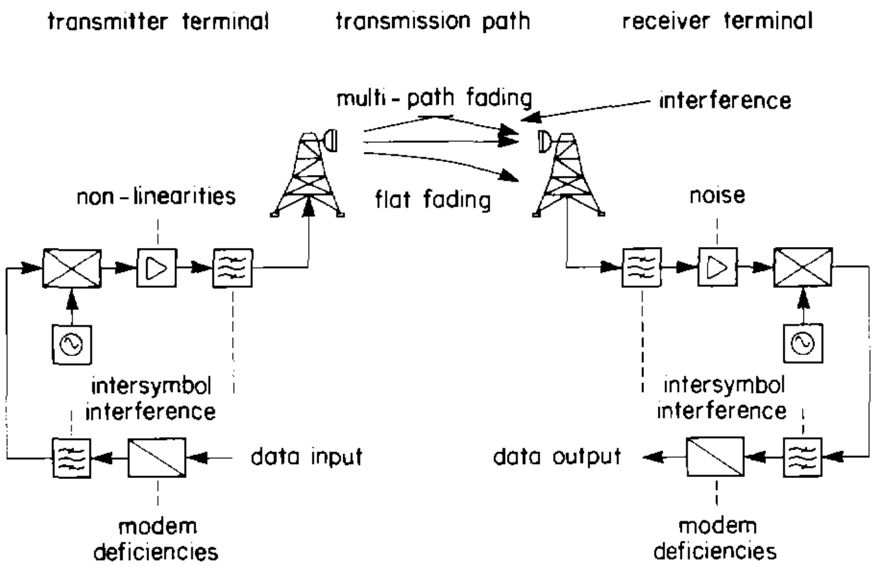

Fig. 1 - A terrestrial digital radio link and its primary impairments.

3.1 The transmitter

The input data is modulated onto an intermediate frequency (IF) carrier. The IF signal is then mixed to the desired transmit frequency in one or more stages. The raw output of the modulator is wideband, (theoretically it is of infinite bandwidth with a sin(x)/x spectrum), and so quite unsuitable for transmission. The IF filter is the primary shaping filter and is used to determine the radiated spectrum. In most systems, this filter will be designed, in conjunction with the shaping filter in the receiver, for zero intersymbol interference (ISI). The zero ISI case occurs when the signal spectrum shape at the demodulator satisfies the Nyquist criterion[1]. There are a number of spectrum shapes which satisfy this criterion.

A class of shapes that is commonly used is cosinusoidal. The filter shape must be skew-symmetric around a frequency half the symbol rate higher and lower than the carrier frequency. One of a family of cosinusoid shapes can be chosen and affects the bandwidth occupied by the signal. Each one is defined by the cosine roll-off factor (CRO) and can vary between 0 and 1. Ideally a low value of CRO would be used to minimise the bandwidth occupied by the signal; however as the CRO becomes lower, the system becomes increasingly susceptible to timing errors and practical filters become more difficult to realise. Practical values of CRO are usually between 0.25 and 1.

The choice of roll-off factor will be determined by the need to tailor a digital radio system to fit the channel spacing of the allocated frequency band. The final selection will always be a compromise between simplifying equipment requirements (large CRO) and minimising occupied bandwidth (small CRO).

Where a simple system, e.g. Quadrature Phase Shift Keying (QPSK) cannot be fitted into a channel spacing by means of reducing the roll-off factor alone, then a more complex modulation system such as 16- or 64-state Quadrature Amplitude Modulation (16-QAM or 64-QAM) will be required.

Digital modulation systems which have amplitude variations in their envelopes (such as QAM systems) are more sensitive to non-linear distortion than constant envelope systems (such as Minimum-Shift Keying (MSK), Tamed FM (TFM) and Frequency-Shift Keying (FSK) systems). This is because in QAM systems non-linear distortion results in regeneration of the sidebands of the original spectrum which had been filtered out. In many cases the effect of this regeneration in the time domain is the introduction of ISI. These effects are usually controlled by operating the devices 'backed off' from their saturated power levels. Further discussion of different modulation methods lies outside the scope of this Report and can be found in Ref. 2.

The RF channel filter rejects the image product from the up-conversion process and in a multi-channel system would provide isolation between the other transmitters. A flat amplitude and delay characteristic over a wider bandwidth than the IF filter ensures that the signal remains free from ISI.

3.2 The transmission path

Fading in which the entire channel bandwidth suffers equal attenuation is referred to as 'flat fading' or 'attenuation fading'. Over microwave links it is typically caused by a change in the normal tropospheric refractive index slope giving rise to either sub-refraction or super-refraction. At higher frequencies, (i.e. greater than 10 GHz), significant fading can be caused by rain or other precipitation. Flat fading does not introduce signal distortion, but for severe fades the link will be degraded by the reduction in signal-to-noise ratio (*S/N*) at the receiver.

Multipath (dispersive) fading occurs when the signal is received by two or more different paths. The delay causes carrier reduction at some frequencies and enhancement at others. Over microwave links this usually results from abnormal propagation conditions in which discontinuities in the tropospheric refractive index slope occur. This gives a layered structure which causes the transmitted signal to traverse several different paths between the transmitter and receiver simultaneously. To model this effect, it is normal to consider only the direct path and a single delayed path. When these two signals combine at the receiver they can produce amplitude and phase distortions in the form of a notch in the spectrum of the wanted signal. The depth of the notch depends on the relative amplitudes of the two signals. Its width varies according to the delay between them, and the centre frequency relative to the wanted carrier depends on the phase shift. The effect of this distortion is an increase in ISI. Digital errors can then occur even when the *S/N* at the receiver is high and no other interference is present.

Interference is the third problem which can cause failure of a link. The effect of interference and methods of controlling its level are covered in considerable detail later in Section 4.

3.3 The receiver

The RF filter provides the first-line rejection of out-of-band noise and interfering signals. The signal can then be split so that the different channels can be mixed to appropriate IFs. For optimum overall performance, the required Nyquist filtering of the link should be shared equally between the transmitter and the receiver. So the IF filter has a similar characteristic to the one at the transmitter.

In the terminal shown in Fig. 1, there is a low-noise RF amplifier prior to the mixer. The carrier-to-noise ratio (*C/N*) is largely determined by the noise introduced by this RF amplifier and the losses in the RF filter. After amplification the signal is mixed to a suitable IF, filtered and in many cases amplified before demodulation. The demodulator regenerates the binary data and clock from the coded IF signal.

Receiver sensitivity is usually characterised by a plot of bit-error ratio (BER) against receiver input signal level. When the link is unfaded, the high *C/N* at the demodulator will result in only a few background errors (a BER of less than 1×10^{-10}). If error correction is used, then the low level background errors can be further reduced. The link between receiver sensitivity and *C/N* is established because the RF filters and amplifiers are part of the equipment and so their noise figures and losses are constant.

3.4 Link budgets

There are three general causes of link failure:

a) fading or interference due to adverse propagation conditions over the link;

b) equipment failure or faults;

and c) human error.

When planning a link, it is desirable to apportion the total link unavailability between these causes. Point (b) can be covered if sufficient information is available about the reliability of each piece of equipment and the electricity supply. Good system design incorporating redundancy is used to allow some faults to be tolerated without loss of the link. Point (c) is much harder to estimate as it relates to the procedures used. Considerable time and effort can be devoted to making accurate calculations of the time the link is unavailable due to adverse propagation conditions.

The link budget calculation provides a means of predicting the signal level at the receiver and hence the system performance. Allowance can be made in the link budget for flat-fading, interference and multipath. It is usually used to allow various link parameters to be determined, such as antenna gains, transmit powers, etc. to achieve the required standard of performance.

For an unobstructed path, the link budget is:

$$P_r = P_t - F_t + G_t - P + G_r - F_r$$

P_r = Receiver Signal Level, dBm
P_t = Transmitter Output Power, dBm
F_t = Transmitter Feeder Losses, dB
G_t = Transmitter Antenna Gain, dB
P = Free Space Path Loss, dB
G_r = Receiver Antenna Gain, dB
F_r = Receiver Feeder Losses, dB

If link parameters were to be chosen such that under normal conditions only the minimum signal level was obtained at the receiver, then any incidence of fading would immediately result in a service outage.

A margin is required to protect the link from fading and this is provided by operating the link so that under normal conditions, the receiver signal is greater than the minimum required. This enhancement in signal over the minimum required, is called the 'fade margin'. An adequate fade margin is the fundamental defence against all types of fading. This is because it is very unlikely for multipath fading to result in link failure on its own. It is usually a contributory factor which increases the susceptibility of the link to noise. A simultaneous flat fade then causes link failure. However an increased fade margin decreases the likelihood of a simultaneous flat fade, thus improving reliability. On the rare occasions where multipath fading is sufficient to cause link failure on its own, an increase in fade margin does not increase reliability. An increase in link availability is usually achieved in these cases by using frequency or spatial diversity or a channel equaliser in the receiver.

When large amounts of multipath fading are present, the receiver *C/N* characteristic alone cannot be used to gauge the effect of the fade, as it is the signal distortion that is the dominant effect. A second receiver characteristic is needed, which shows how sensitive or immune the receiver is to multipath fading. The 'signature diagram' was devised to meet this need. It is a plot of notch (fade) depth against frequency offset of the notch from the carrier. The locus indicates the maximum fade that can be tolerated without degrading the link beyond a particular BER. It is a two-ray model of the link and, whilst it bears little resemblance to the propagation conditions over a real link, it allows comparison of the ruggedness of equipment to multipath.

This Report does not attempt to tackle the problem of the interference protection requirements of a link for which the principle cause of failure is multipath fading.

The severity and frequency of fading events is statistically related to the physical properties of the transmission path and the parameters of the link. Physical properties, such as frequency band, climate, season, weather, terrain, and path length are all important. Link parameters such as data rate, modulation system and receiver sensitivity affect the way in which a link copes with a given set of propagation conditions. Propagation models based on data acquired from both experimental and operational links, are used to estimate the fade margin required to achieve a performance target for a particular system.

There are, of course, practical limits to what can be achieved. For example, high transmit powers are not easily achieved at SHF, but this can be compensated by using high-gain antennas. However, these have a large physical size which exerts a considerable windload on the support structure. They also have a narrow beamwidth, which means that the support structure must resist the slightest deflection to avoid a reduction in the signal in the desired direction.

4. FREQUENCY ASSIGNMENT CONSIDERATIONS

The discussion so far has been limited to the operation of a single link in isolation, but of course, this ideal situation is rarely encountered in practice. The demands placed upon the limited spectrum available for private-user fixed links inevitably lead to crowding in some areas. The luxury of an exclusive frequency allocation is not possible as frequencies have to be re-used. Since any interference from co-channel or adjacent-channel signals is likely to degrade the link, frequency re-use must be carefully co-ordinated to avoid these problems as far as possible. This section deals with the primary factors that influence the planning of frequency assignments.

4.1 The effects of interference

The amount of interference that can be tolerated depends on the sensitivity of the system and the type of interference experienced. For example, complex modulation schemes are more sensitive than the simpler ones, and digitally modulated interference has a different effect from analogue interference.

The amount of signal degradation caused by interference depends on the following factors:

a) the level of the interference;

b) the relative spectral widths of the signals;

and c) whether the spectrum shape of the interferer is fairly uniform across the bandwidth of the wanted signal.

Point (b) is important because if the bandwidth of the wanted signal is significantly narrower than that of the interferer then much of the interference power is rejected by the receiver filter. Point (c) is true for digitally-modulated systems, however analogue modulated signals tend to have spectrum shapes that are uneven and dependent upon the instantaneous signal information.

Interference to digital signals increases the BER. The nature of the interference may determine whether these errors are random or occur in bursts.

If interference to an analogue signal is wideband and has a relatively uniform spectrum shape, then the degradations look noise-like. If it is relatively narrowband then patterning of the wanted signal may result, leading to more stringent protection requirements.

As the effect of interference is to degrade the wanted signal, its presence can cause a signal which is above a quality threshold to be degraded to below that threshold. That is, it can cause the link to fail. Thus, it is important to know the combined effects of noise and interference on the overall signal quality.

4.2 Interference protection methods

The sensitivity of a system to interference is expressed in terms of a protection ratio. This defines the level of interference relative to the wanted carrier, the carrier-to-interference ratio (*C/I*), that will cause a particular degradation to the link. To have any meaning, a protection ratio must include the conditions to which it relates:

> Type of wanted system, type of interfering system, frequency offset, receiver BER without interference, and the amount of degradation that is acceptable.

For co-channel interference, the best possible protection is afforded by a large geographical separation between links having the same frequency assignment. To guard against interference resulting from abnormal propagation conditions, it might be necessary to maintain a separation of, say, 150 km or more to any adjacent link.

This simplistic approach is contrary to the previously noted need for efficient re-use of frequencies. Fortunately there are other mechanisms that can be used to improve the re-use of frequencies.

Firstly, the directional properties of antenna radiation patterns are beneficial at both ends of the link. At the transmitter, the signal is concentrated towards the intended receiver, and at the receiver, the antenna provides discrimination against unwanted interfering sources in directions different to the wanted signal.

Secondly, links are normally operated with either vertical or horizontal polarisation, and so it is possible to make use of the ability of antennas to discriminate between these two orthogonal polarisations. Modern high performance antennas, which have lower levels of radiation in unwanted directions (a mandatory requirement for all new links), can give polarisation discrimination of 25 to 30 dB.

These characteristics are an important part of the frequency assignment process, which explains why antennas for use in private-user bands must meet the performance specifications issued by the RA.

For adjacent-channel interference, all the measures used to protect from co-channel interference also apply. Additionally, the frequency separation between the wanted and interfering signal can also be exploited. The contribution of this benefit to the overall protection required increases as the interferer is offset from the wanted signal. It is zero in the co-channel case, but the spacing will eventually be sufficient to give adequate protection on its own. This frequency spacing is known as the 'minimum co-polarised spacing' or in its short form, 'co-polar spacing'. It is significant, because it determines the channel spacing necessary for these particular systems to be operated on the same route.

It is possible for two systems to be operated at less than the co-polar spacing, but in that case, some other means of making up the short-fall in protection ratio is required. The use of orthogonal polarisations would satisfy this requirement, and gives a reduced spacing known as the 'minimum cross-polarised spacing' or 'cross-polar spacing' for short. Systems can be operated over the same route using cross-polar spacing but it is usually successful only if the same antennas can be used at each end of the link.

For links which are not on the same route but share a receiver site, any frequency offset is possible. In practice, these are assigned in multiples of 3.5 MHz because the private-user bands of interest are normally assigned using channels spaced at a minimum of 3.5 MHz apart. The remainder of the required interference protection is made up from a combination of cross-polar discrimination and antenna radiation pattern discrimination.

A similar situation exists for the more general case when the links are geographically separate. But now there is the additional complication of estimating the interference at the wanted receiver from the remote interfering transmitter, over a path which may not be clear of obstructions.

5. WHAT NEEDED TO BE DONE

To introduce new, high-capacity modulation systems it was necessary to determine the protection ratios required for interference to and from existing systems. Protection ratios can only be found once the acceptable degradation for which protection can be sought has been determined. To put it simply, interference will always introduce some degradation to the signal, even if it is at a very low level, and interference can never be totally eliminated. Therefore it is necessary to decide how much degradation and hence how much interference can be tolerated.

In all practical systems noise and interference will be present and their levels will vary in a statistical manner. It is important to consider not only the cases where interference causes failure of the link on its own, but also cases when the link was close to its failure point due to fading and the addition of a small amount of interference causes failure.

Unfortunately different methods of specifying the amount of degradation that is acceptable are used. This makes comparisons between results determined using these different methods difficult. The method discussed and agreed by the MFLSC for this work was to specify the C/I requiring a given increase in C/N to return to the failure point of the link. Using this approach it is now necessary only to determine a suitable acceptable level of degradation and the failure point of the link.

The agreed level of degradation deemed to be acceptable by the MFLSC is 1 dB.

Determining the threshold of failure of the link was more difficult as it depends on the traffic carried over the link. A threshold BER of 1×10^{-6} was agreed as suitable for most traffic carried on the digitally-modulated systems. It is expected that errors on this scale would cause a noticeable loss of quality on any television signal carried by the link. Although this depends to a large extent on the characteristics of the codecs being used, a BER of 1×10^{-6} probably represents a sensible minimum acceptable standard of performance for this application. It is also the internationally agreed (CCIR and CCITT) threshold on which the performance parameter 'Degraded Minute' is based. It has been used in RA performance specifications to define a minimum standard of receiver sensitivity.

Thresholds can be defined at other BERs such as 1×10^{-4} and 1×10^{-8}. In some cases the protection ratio at these thresholds may be more suitable and so, wherever possible, additional tests have been carried out at these thresholds to cater for the needs of other traffic.

By considering these basic link parameters and frequency assignment criteria, an agreed schedule of tests was evolved that should serve the needs of frequency planners.

The basic format for all the interference tests, was to determine the protection ratio for a 1 dB degradation to the receiver sensitivity characteristic at a suitable chosen failure point. For digital systems, the primary C/N point chosen was that which gives a BER of 10^{-6}. For analogue systems, a C/N point was chosen which represents the minimum acceptable signal-to-noise ratio on the link traffic. This basic test was conducted with the interference co-channel and then repeated at frequency offsets in 3.5 MHz steps. Ideally the tests should continue until the offset is sufficient to permit levels of interference 40 dB to 46 dB greater than the wanted carrier. This was to cater for the worst case situation where the wanted signal and interferer are on the same route and co-polarised, and the wanted signal is faded but the interferer is not. (40 dB represents the maximum allowable fade margin in the 7 GHz band and 46 dB is the maximum allowable fade margin in the 13/14 GHz bands.)

In many cases, the measurement sequence was repeated for more severe degradations of 2 dB and 3 dB. Wherever possible, additional points on the receiver C/N characteristic (equivalent to BERs of 1×10^{-4} and 1×10^{-8}) were also used. This resulted in a matrix of nine tests to be performed at each frequency offset.

Before any experimental measurements could be made it was necessary to measure the performance of each of the systems. This verified that the systems were working properly.

It was recognised that the protection ratios obtained from this sort of test would be specific to the particular types of equipment tested. For this reason, the raw results were not intended to be used on their own for frequency assignment purposes. Instead, the experimental and calculated results should be compared. On their own, calculated results provide values which are independent of the vagaries of particular pieces of equipment; however they may bear little relation to real measured results because some factor might have been neglected in the calculation. Measured results record the performance of real equipment; however they give no idea of whether the result is general for all equipment of that modulation format, or specific to that particular manufacturer's design or even one specific piece of equipment. For this reason both calculated and measured results were obtained. A suitable set of protection ratios could then be determined as a synthesis of these results.

6. THEORETICAL CALCULATIONS

The aim was to calculate the performance of various modulation systems. Calculations were made using parameters corresponding to those of the experimental modems; it was hoped that these results would agree with the experimental measurements. The calculations could then be extended to allow differences in the various parameters to be examined, in particular, the effect of an interfering system which exactly and completely filled the permitted interference mask could be considered. Such calculations would allow us to examine the differences between the typical interference protection results and the worst-case requirements that could occur.

These tests considered both digital and analogue modulation systems as both wanted and interfering signals. Therefore, there were four distinct cases that could be examined.

The first priority was to consider the case of interference into digital systems:

(a) from other digital systems;

and (b) extending the work to consider interference from analogue systems.

An entirely different set of calculations would be required to consider interference into analogue systems:

(a) from digital systems;

and (b) from other analogue systems.

These four cases were further complicated because many practical systems use analogue or digital subcarriers; this results in multiple failure points for the system.

This section considers the first two cases only, i.e. interference into digital systems from both analogue and digital interferers.

Some work was conducted to extend this work to consider interference from digital links into the primary video signal of an analogue link. However initial results did not show close agreement and further work has not been possible at the time of writing. Therefore calculations covering interference into digital systems only will be presented in this Report.

6.1 Basis of the calculations

The form of the calculations was to find the level of interference required, at a particular frequency offset, to produce a degradation in the noise performance of the system at a particular threshold point. This point was chosen to be at the edge of failure for that system. To put this more simply: first decide a suitable failure point for the system, next calculate the *C/N* for that modulation system which would result in the system operating at that failure point. Then decide the amount of degradation in performance that is permissible; the *C/N* in the calculation is then increased by that amount, resulting in an improvement in the system performance. Interference is then added, at the desired offset frequency, until the calculations show that the failure point has been reached again. For example, consider a QPSK system and decide that a suitable failure point is a BER of 1×10^{-6}. The corresponding failure point for a theoretical system can be found to be an E_b/N_o* of 10.5 dB. Assuming that a 1 dB degradation in the performance of the system was acceptable, the level of the interference could then be calculated, the result would, of course, depend on various details of the parameters.

It can be seen that these calculations allow for the combined effects of noise and interference on the modulation system; however no consideration of multipath performance has been made. The results directly follow the experimental tests that were performed and so should give reasonable agreement. However, when using them to find the overall performance of a link multipath must be considered.

The calculations in this Report are based on earlier work discussed in Ref. 3. In this the work of Rosenbaum[4] and Prabhu[5] is discussed. Starting from the case of a single sinusoidal interferer, the analysis is extended to a number of equal-power interferers. Prabhu's work notes that if the interference power is concentrated in a single interferer then least degradation to a wanted signal will occur.

Conversely, if the interfering power is spread among more interferers the degradation will increase. The limiting case, which causes the largest degradation to the wanted signal, occurs when the interfering power is spread evenly across the frequencies of interest; this corresponds to the case of Gaussian noise. Therefore an upper and lower bound of system performance was established in Ref. 3; the upper bound assumed that the interfering power was concentrated in a single unmodulated carrier, and the lower bound assumed the interfering power had a distribution corresponding to that of Gaussian noise. This approach obviates the need to perform complex calculations for large numbers of interfering, unmodulated carriers.

In this work we concentrated on developing algorithms to perform the calculations assuming the interfering signal to have a Gaussian distribution. The reason for this was that firstly this represented a worst case, i.e. practical systems should be more tolerant to interference than this, and secondly because the spectral occupancy of the interfering signals was such that the Gaussian noise case should give closer answers. If time had permitted, we planned to extend the analysis to consider the case of sinusoidal interference into the various digital modulation systems. The equations for sinusoidal interference into a BPSK and QPSK system are given in Refs. 3 and 5. These would have to be extended to allow interference into higher level QAM modulation systems to be considered.

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* E_b/N_o is the ratio of the energy per information bit and the noise spectral density. It corresponds to the *C/N* measured in a bandwidth corresponding to the data rate.

The first extension of the work described in Ref. 3 was that the algorithms should deal with different digital modulation systems with different data rates, filter shapes and transmitted spectrum shapes. It was decided to confine the allowable types of digital-modulation system to the those using different levels of QAM as this covered all the digital modulation types used in the tests with the exception of the MSK system. The MSK system could be modelled approximately as a QPSK system.

The second requirement was that the algorithms should allow the interfering signal to be specified as a hypothetical signal exactly filling an interference mask. This would allow the effect of systems which just met the permitted mask, but were worse than the typical ones measured in the experiments, to be assessed. This extension also allowed the worst-case effect of interference from analogue signals to be considered, as masks for the analogue signals were available. More representative calculations to duplicate the experimental work were not considered because of the problem of defining the spectrum of the interfering analogue signal more closely.

6.2 Algorithms used

The first step was to calculate the E_b/N_0 corresponding to the required failure points. Three different BERs had been suggested as suitable failure points and were examined in the experimental work, these were 1×10^{-4}, 1×10^{-6} and 1×10^{-8}. Therefore the E_b/N_0 at all three failure points was calculated. The BER and E_b/N_0 in a QAM system are related[4] by the equation:

$$\text{BER} \approx \left(1 - \frac{1}{\sqrt{M}}\right) \operatorname{erfc}\left[\sqrt{\frac{3\gamma}{2(M-1)}}\right]$$

where:

M is the number of phase states in the QAM system

γ is the ratio of energy per symbol to noise spectral density

γ is related to the E_b/N_0 by the formula:

$$E_b/N_0 = 10 \log\left[\frac{\gamma}{k}\right]$$

where:

k is the number of bits per symbol

The level of interference required to produce the specified degradation in the E_b/N_0 can now be calculated. The following parameters were required for this calculation:

wanted signal:

- modulation type
- data rate
- FEC code rate
- roll-off factor of the filtering
- implementation margin of the modem*

Interfering signal parameters which were of interest depended on whether the signal spectrum was modelled on the theoretical spectrum or an allowable interference mask. In the latter case the mask shape was specified, in the former case the following parameters were required:

- modulation type
- data rate
- FEC code rate
- roll-off factor of the filtering

The carrier-to-interference ratio, where the interference power is that at the output of the receiver filter can be found from:

$$C/I_{\text{filter out}} = 10 \log\left[\frac{10^{(C/N+a)} \cdot 10^{C/N}}{10^{(C/N+a)} - 10^{C/N}}\right] + imp$$

where:

C/N is the E_b/N_0 of the particular threshold of interest for the modulation system of interest, dB

a is the allowable degradation in C/N performance (1 dB, 2 dB or 3 dB)

imp implementation margin of system, dB

The relationship between the true C/I of the signals at the input to the receiver, and the ratio of powers at the output of the receiver filter can be found from:

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* The implementation margin is the amount by which the practical, realisable performance of the modem falls short of theory. The more common causes are non-ideal filtering, phase error in the carrier or clock recovery circuits and noise contributions added in the receiver. Small implementation margins (given in Appendix 1) were allowed for all systems in these calculations as they will be present in all practical systems.

$$C/I = C/I_{\text{filter out}} + 10 \log \left[\frac{\int_{-\infty}^{+\infty} i(f) \cdot r(f) \cdot df}{\int_{-\infty}^{+\infty} i(f) \cdot df} \right]$$

where:

$i(f)$ is the interfering spectrum shape as a function of frequency

$r(f)$ is the receive filter shape as a function of frequency

In the case of calculations assuming theoretical filters and spectrum shapes these functions are given by:

$$i(f) = 1 \qquad \text{for} \quad |f-f_0| < h_{\text{int}} \cdot (1-c_{\text{int}})$$

$$i(f) = 0.5 \cdot [1-\text{Sin}(\pi \cdot (|f-f_0| - h_{\text{int}})/(2 \cdot c_{\text{int}} \cdot h_{\text{int}}))] \qquad \text{for} \quad |f-f_0| > h_{\text{int}} \cdot (1-c_{\text{int}}) \quad \text{and} \quad |f-f_0| < h_{\text{int}} \cdot (1+c_{\text{int}})$$

$$i(f) = 0 \qquad \text{for} \quad |f-f_0| > h_{\text{int}} \cdot (1+c_{\text{int}})$$

$$r(f) = 1 \qquad \text{for} \quad |f-f_0| < h_{\text{wtd}} \cdot (1-c_{\text{wtd}})$$

$$r(f) = 0.5 \cdot [1-\text{Sin}(\pi \cdot (|f-f_0| - h_{\text{wtd}})/(2 \cdot c_{\text{wtd}} \cdot h_{\text{wtd}}))] \qquad \text{for} \quad |f-f_0| > h_{\text{wtd}} \cdot (1-c_{\text{wtd}}) \quad \text{and} \quad |f-f_0| < h_{\text{wtd}} \cdot (1+c_{\text{wtd}})$$

$$r(f) = 0 \qquad \text{for} \quad |f-f_0| > h_{\text{wtd}} \cdot (1+c_{\text{wtd}})$$

where:

h is one-half the symbol frequency of the wanted (wtd) or interfering (int) signal

c is the cosine roll-off factor (measured as a fraction) of the wanted (wtd) or interfering (int) signal

The half-symbol rate is related to the information rate (α) and the FEC rate (β) of the modem and the number of phase states of the QAM modulation (M) by the expression:

$$h = \frac{\alpha}{2\,\beta \log_2 M}$$

In the case where interfering signals were assumed to follow a specified mask, i(f) was taken to be the mask shape. However, in this case a change was required; if the integral had been taken from minus infinity to plus infinity then an infinite power would have resulted, therefore the integral was taken between the frequencies where the mask reached its ‘floor’.

6.3 Assumptions used in the calculations

A number of assumptions have been made in these calculations. The first, which has already been mentioned, is that the spectral distribution of the signal approximates to that of Gaussian noise. The limitations of this assumption will depend on the relative spectral widths of the wanted (or victim) and interfering signals and their relative frequency offset. If the interfering signal occupies most of the width of the victim's receive filter then the approximation should be a good one. However, if the spectral width of the interfering signal is much narrower than that of the victim then an error is likely. In this case, the calculated result should indicate that the system is more sensitive to interference than is the case in practice, i.e. for planning purposes this is a worst-case situation.

The second assumption is that the modems use theoretical Nyquist spectral shaping of the transmitted signal and filtering of the received signal. It is also assumed that the filtering is optimally distributed for noise considerations, that is, the filtering is equally split between the transmitting and receiving halves of the modem. Practical filters do not satisfy these criteria exactly and so an error will result. It is anticipated that this approximation will be satisfactory for the in-band filter shape but that out-of-band errors may result. In particular, the theoretical receive filter out-of-band response is zero, whereas all practical filters have a finite (albeit small) out-of-band response. Therefore these calculations will predict that an infinite level of out-of-band interference can be tolerated whereas in practice the result will be finite. Part of this limitation is overcome by the use of interference spectrum masks in the second half of the calculation, as these represent a worst-case permitted interfering spectra. However the filter responses of all the modems were not available so it was not possible to perform more representative calculations. In any case, more equipment-specific calculations should give more accurate answers but are arguably less representative for planning purposes.

The final assumption relates to the way in which the calculation is performed when the victim modem incorporates Forward-Error Correction (FEC). In this case, the channel error rate corresponding to threshold information error rate is found. The E_b/N_0 at the channel error rate is then used in the calculation.

So, for example, if error correction results in a corrected BER of 1×10^{-6} (which is the required threshold) occurring at a channel BER of 1×10^{-4}, then the E_b/N_0 at the channel BER of 1×10^{-4} is found and used in the subsequent calculations.

Using these assumptions, calculations were performed for the various combinations described at the start of this section. The parameters assumed for each modulation system and the interference masks are listed in Appendix 1.

7. EXPERIMENTAL MEASUREMENTS

The details of the radio systems tested in these experiments are listed in Appendix 2.

7.1 Test arrangement

An experimental arrangement was assembled that could be used for all the sets of tests. This arrangement is shown in Fig. 2. The wanted and interfering signals are both mixed to a common IF of around 1.5 GHz. They can be individually adjusted in level before being combined. Noise is added and the total signal is mixed back to the required receive frequency. A spectrum analyser is used to observe and measure the relative levels of the signals.

This complicated arrangement is required to allow the various tests to be conducted with one set-up; these tests were both to characterise the systems and measure their interference performance. Appendix 2 shows that the systems operate at very different frequencies. However they could all be measured with this arrangement (except the 3.5 MHz narrowband video system which was interfaced directly to the experimental arrangement at its IF).

Three types of measurement were performed. The first was to measure the output signal performance as the input signal level was reduced. The second was to maintain the input signal level but add Gaussian noise to it and observe the output signal performance as the noise level was increased. Both these tests were performed in the absence of interference. The third measurement was to add interference to the signal when it is a known distance from a failure point and measure the amount of interference required to return the output signal to that failure point.

The first two measurements were performed to characterise the systems so as to check that they were working correctly. The third measurement was the purpose of the tests.

Oscillators having high stability and low phase noise were required to ensure that the signals were not degraded in the mixing processes. Filters were required

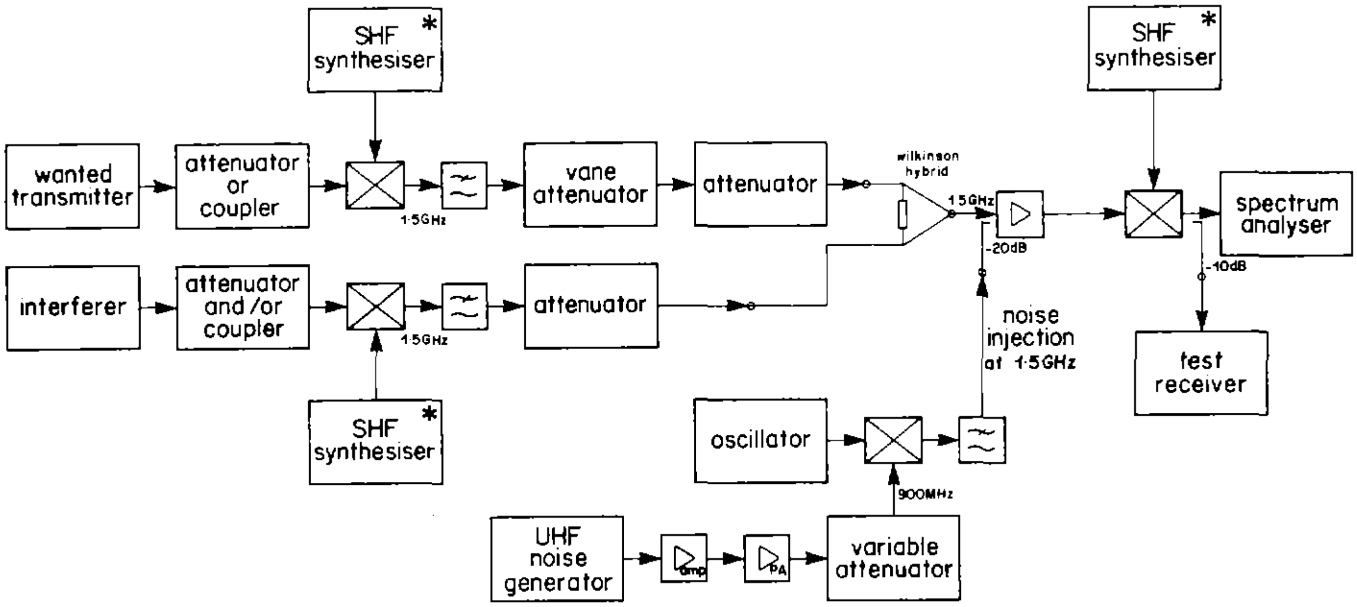

Fig. 2 - Experimental arrangement.
* High-stability, low-phase noise

to reject the mixing products and precision step attenuators were used to ensure that the *C/N* of the wanted signal and the interferer could be increased by exact amounts. The Gaussian noise was generated at UHF because a suitable noise source was readily available at these frequencies.

7.2 Characterisation of systems

In the first of these tests the input signal was reduced and the output signal quality measured. In the case of the digital systems, the output signal BER was measured and in the case of the video systems, the signal-to-noise ratio was measured. The input signal power to the receiver was measured using a combination of a power meter and spectrum analyser. This combination was used because the signal at the input to the receiver contained image and local oscillator breakthrough frequency components. These extra components did not affect the performance of the systems as they were filtered out in the receiver, however they prevented a true measurement from being made directly on the power meter. The spectrum analyser could not be used directly for two reasons, firstly because it does not read the total power in the modulated signal correctly and secondly because its accuracy when making absolute power measurements was doubtful. The difference in power level between the modulated and unmodulated signals was found using the power meter. The spectrum analyser was calibrated using the unmodulated carrier. Measurements of unmodulated carrier level could then be made using the spectrum analyser and corrected to find the true modulated power level.

The second set of tests performed to characterise the system under test, added Gaussian noise to cause system failure. The advantage of these tests was that the E_b/N_0 could be measured and the performance of the system compared directly with theory. The problem with these measurements was in obtaining gaussian noise over a sufficient bandwidth and then measuring the signal and noise powers accurately. The noise power was measured using a facility provided on the spectrum analyser. Measurements on other projects had confirmed that this method gives repeatable results but that a systematic error of up to ±2 dB may be introduced; this error depends on the spectrum analyser settings used for the experiment and could not easily be calibrated out on this occasion. The method of measuring the signal power has already been described earlier in this section; however, in this case, the absolute power is unimportant as both the signal and noise powers were measured on the spectrum analyser.

The procedure used was to increase the input signal level to between 10 dB and 20 dB above the level required to produce failure in the first test. Noise was then added until the failure point was reached. The input RF signal was examined to ensure that the noise was flat over the required bandwidth and that no spurious signals were present in-band. A set of measurements was then made. The output baseband signal performance with signal modulation present was measured and then the E_b/N_0 was measured with the signal unmodulated. The adjustment was then made to give the E_b/N_0 that would have been present with the signal modulated.

7.3 Interference tests

This comprised the majority of the work. The experimental arrangement shown in Fig. 2. was used. Before a set of measurements was made, the difference in power output for each system with the signal modulated and unmodulated was noted. The *C/I* could be measured accurately using the spectrum analyser with the signals unmodulated and the performance of the signal under test was measured with the signals modulated. The measured *C/I* could then be adjusted to account for the differences in power between the modulated and unmodulated signals.

For the digital victims, the tests were performed at threshold BERs of 1×10^{-4}, 1×10^{-6} and 1×10^{-8} and measurements were made of the *C/I* required to produce 1 dB, 2 dB and 3 dB degradations in *C/N* performance at each of these thresholds. The only exception was that a full set of measurements was not made for the low data rate systems. The measurements at a BER of 1×10^{-8} were not conducted as they were very time-consuming to make. This is because at low BERs a long averaging time is required to obtain consistent results.

For the analogue victims, the measurements were made of the interference required to produce a 1 dB, 2 dB and 3 dB degradation in the *C/N* at a threshold video *S/N* (unweighted) of 32 dB for the 3 MHz surveillance video and 35 dB for the TV video. The Radar remoting video equipment and 300-channel FDM system could not be made to operate satisfactorily and so no measurements were made with these systems as victims. The TV video system is further complicated as there are a number of different methods of carrying sound carriers. The failure of these systems also had to be considered.

Four audio systems were examined, these were:

- two analogue audio signals, carried individually on subcarriers
- four analogue audio signals, carried individually on subcarriers

- three stereo pairs of audio signals, carried as a 2 Mbit/s digital signal TFM on a single subcarrier
- one stereo pair of audio signals, carried as a 728 kbit/s digital signal in the television synchronising pulses, known as dual-channel sound-in-syncs (SIS).

The failure points of these systems were taken to be an unweighted audio *S/N* of 35 dB on the highest frequency carrier in the first two cases, a BER of 1×10^{-4} for the TFM signal and a BER of 1×10^{-5} for SIS. The highest frequency carrier was used in the first cases as it suffered most from the triangular-shaped noise spectrum produced by the FM demodulator.

Before any measurements were made using a particular combination of victim and interferer a number of checks were made. The levels of the signals were checked to ensure that the required dynamic range could be obtained. A range of approximately 70 dB was required for the interfering signal and in most cases it was found to be practical to obtain a range of around 60 dB. The interfering signal was checked for spurious outputs. The wanted and interfering signals were checked to ensure that no significant sideband regeneration or other spectrum distortion occurred. The overall system was checked to ensure that no intermodulation products were generated. These checks were all made by observing the signals on the spectrum analyser and were designed to ensure that the experimental system was as transparent as practically possible.

The procedure used in each of the measurements was as follows. The interference was removed and the wanted signal level was reduced until the desired threshold was reached. The modulation was removed from both signals and the level of the interference was increased until the signals were of equal level. The attenuator setting of the interference was noted. The interference was removed and signal modulation was restored. The level of the wanted signal was then increased by 1 dB, 2 dB or 3 dB depending on which measurement was being made.

Interference was then added until the threshold point of the wanted signal was reached. The interference attenuator setting was noted. The procedure was repeated at each threshold BER for each frequency offset.

The estimated accuracy of the measurements is ±2 dB. The interference level could only be adjusted using a step attenuator in 1 dB steps. In addition, any small errors in the step attenuator which was used to increase the wanted signal level by exact amounts would cause a much larger error in the *C/I* result. The latter error is difficult to estimate; however an overall accuracy of around ±2 dB is reasonable.

8. RESULTS

The experimental equipment was only available for a limited period and so the measurements were performed before the calculations were made. In addition, the experimental arrangement had to be dismantled before the calculations were performed and so no retrospective checking of the experimental results was possible. Thus these results were obtained almost totally independently.

The calculated and measured results will be considered separately to begin with, then compared and the differences discussed in more detail. Because of the large amount of data, only occasional sets of results will be included in the main text. The complete set of results for the interference tests, both measured and calculated, for the 1 dB degradation in *C/N* at a BER of 1×10^{-6} is contained in Appendix 4, to which the reader should refer for the particular results of interest.

8.1 Experimental results

The first tests were to characterise the systems and ensure that they were working correctly. These tests were of:

a) the input signal sensitivity or received signal level;

and b) the performance of the system in the presence of artificially-generated noise (expressed as E_b/N_0).

The results were compared with the typical and guaranteed performances given in the equipment specifications in the former case and the theoretical performances in the latter case.

Appendix 3 contains the results from the characterisation tests.

The accuracy of the results is estimated to be ±1 dB and ±2 dB for the receiver sensitivity and E_b/N_0 measurements respectively. However the E_b/N_0 measurements may also have a systematic error. The results from both tests have been presented on the same graph. The received signal and E_b/N_0 x-axis scales have been aligned so that the measured results from both tests form a best fit to the one line. This approach is a little unusual, however the advantage is that it allows the measurements obtained from the two tests to be presented on the same graph.

The alignment between the two x-axis scales could in theory have been calculated; however, in practice, insufficient data was available to allow this to be done. The approach also allows an approximate idea of the noise performance of the receiving system to be found from the relative alignment of the scales on the x-axis.

It can be seen from the results in Appendix 3 that the systems are performing satisfactorily. The measured performances lie between the theoretical and guaranteed practical curves. There are two results worthy of extra comment: in both the 140 Mbit/s QPSK and 140 Mbit/s 16-QAM results, the E_b/N_0 measurements appear to be somewhat optimistic; that is, a slightly lower E_b/N_0 was required to produce a given BER than seems likely. This may be caused by the systematic error mentioned earlier.

Overall these results give confidence that the experimental equipment is performing to its design specification and should give reliable and representative results. They also confirm that the experimental equipment has been well designed and does not have an unreasonably high implementation margin. As a result, the assumption used in the calculations are valid*. No results were produced for the radar-remoting video or the 300-channel FDM equipments because of instrumental problems.

Interference measurements were made and the results are shown as the marked points on the graphs in Appendix 4. The measured and calculated results will be considered in more detail later, however a number of general comments about the measured results can be made. The curves show the expected increasing tolerance to interference as the offset frequency is increased.

Comparison between measurements shows that the systems are more susceptible to interference at the more exacting failure thresholds and less susceptible to interference as the amount of C/N degradation that can be accepted is increased. Both these results were to be expected. The amount by which the systems are more tolerant to interference in each of these cases appears to be largely independent of the frequency offset and modulation system. The reliability of a few of the results is doubtful. These cases have usually been highlighted by comparison with the calculated results but it was not possible to recheck them.

The main problem was that a large range of interference level was required. Linearity through the system was required over the whole range. In most cases a satisfactory combination of levels was found, but inevitably the results obtained using large, negative C/I are less reliable in that they are very susceptible to low-level spurious outputs from the interferer, small amounts of sideband regeneration or other spectrum distortion and other miscellaneous effects. Even if they are perfectly accurate for these sets of equipment then they are likely to be significantly different if different equipment (of identical type and manufacturer) had been used. In any case it was necessary to choose carefully which way to offset the interferer. Some systems produced low-level spurious output on one side of their main spectrum and we could obtain different results depending on whether a positive or negative offset frequency was used. In these cases, the extra components were assumed to be unwanted and not representative; the signal was offset so that they did not affect the result.

In general the results are reliable and show the expected trends. A somewhat larger scatter in the results made at the BER threshold of 1×10^{-8} was observed. This was attributed to the practical difficulties in making consistent measurements at low error rates. An alternative method of measuring the degradation of a digital system is to measure the received signal 'eye height'. This measure is particularly helpful in giving consistent results at low BERs. However, in these experiments, it was not possible to make 'eye height' measurements easily.

8.2 Calculated results

Calculated results for interference from a 140 Mbit/s QPSK system into a 140 Mbit/s 64-QAM system are shown in Fig. 3. This is one set of results chosen to illustrate the general feature of all the results. Fig. 3 shows curves for 1 dB loss of C/N at a threshold BER of 1×10^{-6}. The solid curve shows the expected increasing tolerance to interference as the frequency offset is increased. The curve becomes very steep as the point is reached where the interfering spectrum no longer overlaps with the receive filter.

There are a number of general points which can be noted in the result obtained using spectrum masks. The first is that, whilst the dashed curve is similar to that calculated using an ideal spectrum at small offset frequencies, slightly more interference can usually be tolerated in the mask case. This is because the power in the interfering spectrum is spread to fill the mask, and with some power in the

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* Calculations could have been performed with a large implementation margin. However it would have been unwise to base protection ratio curves on results (whether measured or calculated) from equipment which was considerably worse than could be achieved. In particular, if the large implementation margin had been due to unnecessarily wide receiving filters then results based on such filters would be very misleading.

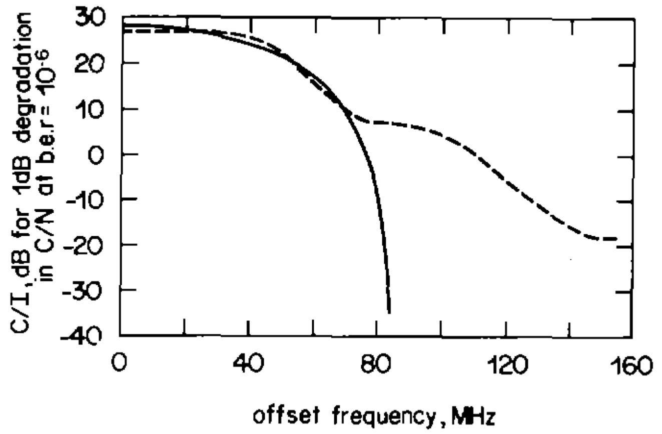

Fig. 3 - Calculated results with theoretical and mask spectrum interference for threshold BER of 1×10^{-6}

Victim: 140 Mbit/s 64-QAM
Interferer: 140 Mbit/s QPSK
——— Calculations based on an ideal system
- - - - *Calculations based on a 'worst case' system masks*

'shoulders' of the mask the peak power density is slightly reduced.

The effect of the mask shoulders on the results obtained using the spectrum mask can be seen. A distinct shoulder can be seen on the resulting curve. However this shoulder on the *C/I* results becomes less distinct as the interfering spectrum bandwidth becomes significantly narrower than the receive filter width. The shoulders on the masks were almost certainly included to allow for a certain amount of sideband regeneration which can occur in practical systems.

A distinct 'floor' can be seen on the curves calculated using the spectrum masks. This floor is due to the floor on the spectrum mask. The floor to the *C/I* results can be seen to be 45 dB lower than the co-channel result. This is to be expected as the floor of the mask is 45 dB lower than the peak value (see Appendix 1 for the masks). Whereas this result may seem self-evident, it is not correct in all cases. Where the receive filter is much wider than the 3 dB bandwidth of the interfering signal mask, the difference between the co-channel result and the floor of the *C/I* results will be reduced by a factor proportional to the ratio of the receive filter-to-interfering signal bandwidths. To illustrate this let us take a simple case, a 'top hat' receive filter x Hz wide with infinite out-of-band rejection and a rectangular interfering spectrum y Hz wide of arbitrary peak power density, a W/Hz, and with an out-of-band floor f dB lower than the peak. The situation is shown in Fig. 4 and in this analysis it is assumed that $x > y$. When the interferer is co-channel the power at the output of the receive filter is given by:

$$P_{\text{co-channel}} = (x - y)\, a\, 10^{\frac{-f}{10}} + a\, y \qquad \text{for} \quad x > y$$

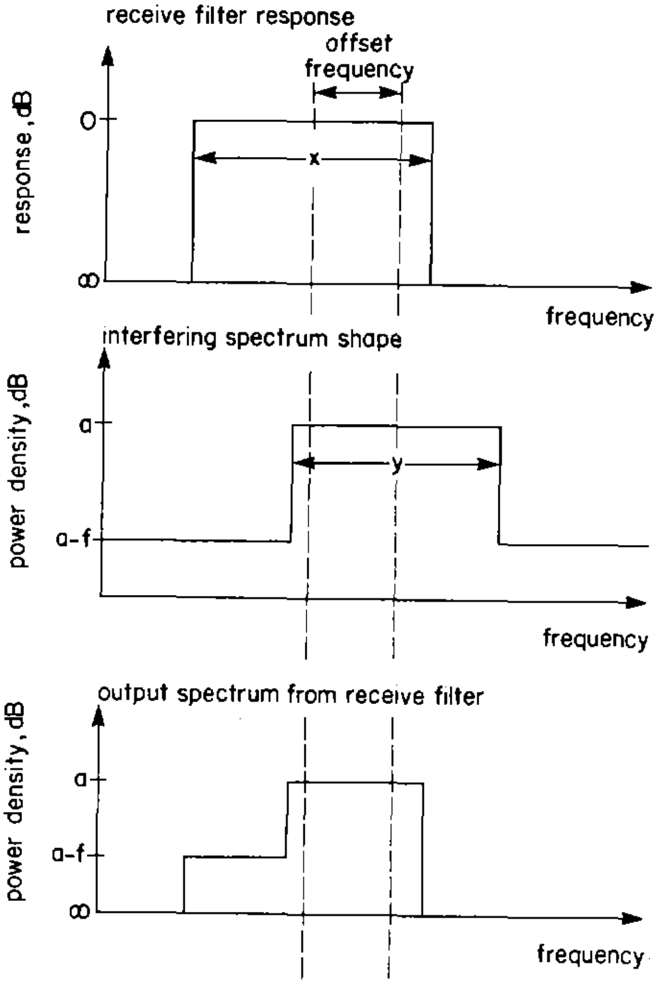

Fig. 4 - Diagram showing the effect of the mask floor on the calculated results.

When the interferer is at a large frequency offset the power at the output of the receive filter is given by:

$$P_{\text{offset}} = x\, a\, 10^{\frac{-f}{10}}$$

The ratio of these output powers gives the difference between the co-channel *C/I* result and the floor at large offsets; this is given by:

$$\frac{P_{\text{co-channel}}}{P_{\text{offset}}} = 1 - \frac{y}{x} + \frac{y\, 10^{\frac{f}{10}}}{x} \qquad \text{for} \quad x > y$$

In most cases the floor of the mask is many tens of dBs below the peak. Thus f is large and so the first two terms of the expression can be ignored. The ratio, expressed in logarithmic form P_{log}, then reduces to:

$$P_{\text{log}} = f + 10 \log \left[\frac{y}{x}\right] \qquad \text{for} \quad x > y$$

When the interfering signal is of the same spectral width as the receive filter, or wider, $y = x$ and the ratio becomes equal to f as expected. When the interference mask is significantly narrower than the receive filter, the floor is reduced by an amount proportional to the ratio of their widths.

This result is exact for the cases of perfectly flat, rectangular receiving filters; however it is only approximate when the receive filter uses a large percentage cosine roll off. The principle remains the same and explains why the floors on the *C/I* results are higher than might be expected in some cases.

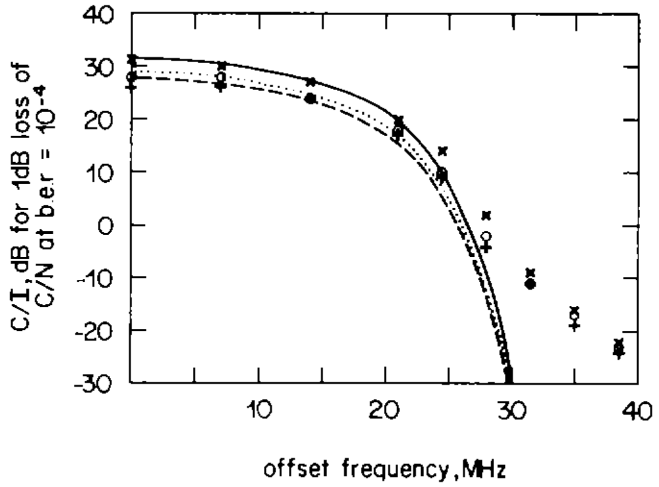

Fig. 5 - Measured and calculated results for theoretical spectrum interference for a threshold BER of 1 × 10^{-4}.

Victim: 140 Mbit/s 64-QAM
Interferer: 34 Mbit/s QPSK

8.3 Comparison of experimental and calculated results

8.3.1 Comparison of results over the range of BER thresholds and *C/N* degradations

The theoretical and measured results can now be compared. We start by considering a representative case; that of interference from 34 Mbit/s QPSK into 140 Mbit/s 64-QAM. Figs. 5, 6 and 7 each show the results for a 1 dB, 2 dB and 3 dB loss of *C/N* at the threshold BERs of 1 × 10^{-4}, 1 × 10^{-6} and 1 × 10^{-8} respectively.

It can be seen that good agreement is obtained between the theoretical and measured results when the interferer is at small frequency offsets. This is particularly true given the estimated experimental accuracy of ±2 dB and allowing for the idealised assumptions used in the calculations. The good agreement is maintained at the various BER thresholds and for the various different losses in *C/N*. This indicates that the calculation models the measured situation well, rather than merely being adjusted to

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Calculations based on an ideal system:

———— 1 dB loss of *C/N*
············ 2 dB loss of *C/N*
– – – – – 3 dB loss of *C/N*

Experimental measurements:

× 1 dB loss of *C/N*
○ 2 dB loss of *C/N*
+ 3 dB loss of *C/N*

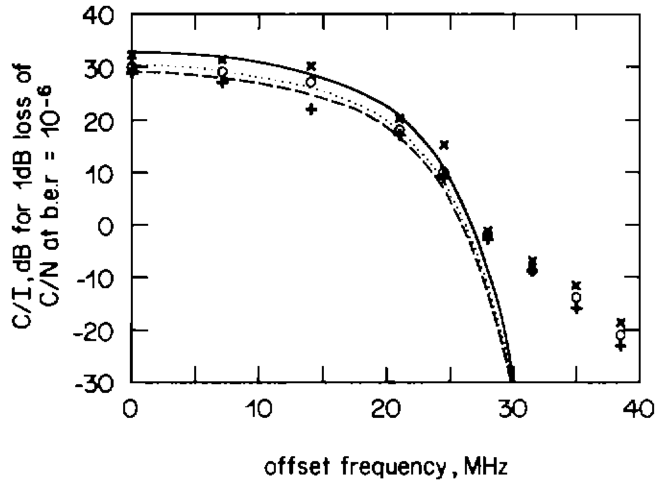

Fig. 6 - Measured and calculated results for theoretical spectrum interference for a threshold BER of 1 × 10^{-6}.

Victim: 140 Mbit/s 64-QAM
Interferer: 34 Mbit/s QPSK

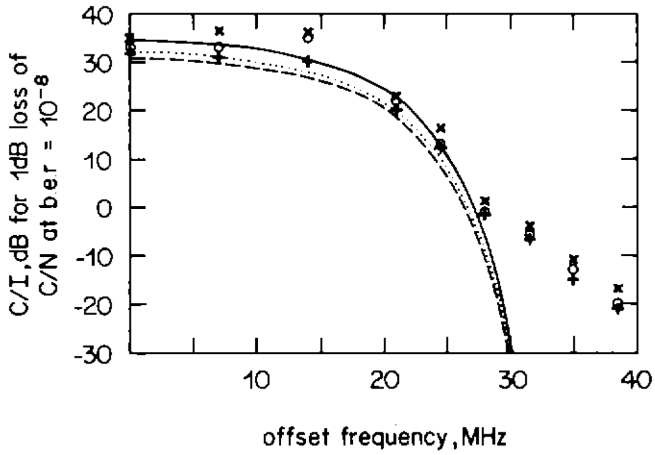

Fig. 7 - Measured and calculated results for theoretical spectrum interference for a threshold BER of 1 × 10^{-8}.

Victim: 140 Mbit/s 64-QAM
Interferer: 34 Mbit/s QPSK

give good agreement at one spot value. The theoretical calculations confirm the experimental observation that the difference in *C/I* between different threshold BERs and amounts of *C/N* degradation is independent of frequency offset.

Larger errors between the results can be seen in Fig. 7 at the BER of 1 × 10^{-8}. This was almost certainly due to the difficulty in making large numbers of accurate measurements at low error rates. Certainly, throughout the measured results, a significantly larger scatter was observed on the results at threshold BERs of 1 × 10^{-8}.

At large frequency offsets a discrepancy between the measured and theoretical results can be seen. This is because the theoretical calculation assumes ideal filtering and spectral shaping which does not occur in practice. In particular, the theory allows an infinite level of interference at frequency offsets where the ideal interfering spectrum and the receive filter do not overlap at all — this does not occur in real life!

The large number of measured and theoretical results makes it impractical to present the results for every combination of wanted and interfering signal, at every offset, for 1 dB, 2 dB and 3 dB losses in *C/N* performance at BER thresholds of 1 × 10^{-4}, 1 × 10^{-6} and 1 × 10^{-8}. Therefore we will present the results for only the 1 dB loss of *C/N* performance at the BER threshold of 1 × 10^{-6}. However it has already been noted that the difference between this 'reference' condition and the other BER thresholds and *C/N* degradations is independent of offset frequency. Examining the theory also shows that the difference is also independent of data rate and modulation type, therefore a correction factor can be produced to allow the *C/I* for the 2 dB or 3 dB losses of *C/N* and the BER thresholds of 1 × 10^{-4} and 1 × 10^{-8} to be found from the 'reference' case. This correction factor is given in Tables 2 and 3; two tables are required because, although the correction factor is independent of modulation type it is not independent of threshold BER and the addition of error correction is equivalent to a change in threshold BER*. A positive correction factor indicates that a higher *C/I* is required in the new condition.

Table 2
Correction factors for systems with no error correction

C/N degradation	Threshold BER 1 × 10^{-4}	 1 × 10^{-6}	 1 × 10^{-8}
1 dB	−2.1 dB	0.0 dB	1.5 dB
2 dB	−4.6 dB	−2.5 dB	−1.0 dB
3 dB	−5.9 dB	−3.9 dB	−2.4 dB

Table 3
Correction factors for the 64-QAM system with rate 81/84 FEC

C/N degradation	Threshold BER 1 × 10^{-4}	 1 × 10^{-6}	 1 × 10^{-8}
1 dB	−1.5 dB	0.0 dB	2.0 dB
2 dB	−4.6 dB	−2.6 dB	−0.6 dB
3 dB	−5.4 dB	−3.9 dB	−1.9 dB

Considering the results so far, we can conclude that good agreement is obtained between the theoretical and measured results at small frequency offsets. As the offset frequency of the interference becomes larger and the interfering spectrum overlaps less with the receive filter, an increasing discrepancy occurs. This discrepancy is due to differences between the ideal and practical interfering spectrum and receive filter shapes. Consistent agreement at the various BER thresholds and *C/N* degradation levels allows us to consider only the results for one case and apply a correction factor to obtain the values for the other cases. The reference case chosen was that of a 1 dB degradation in the *C/N* performance at a BER of 1 × 10^{-6}.

The major discrepancy was at large frequency offsets and was due to the actual receive filter and interference spectrum being non-ideal. The specific problems are that the receive filter shape is not perfect, the out-of-band rejection is not infinite and spurious out-of-band interference is present.

The receive filter characteristics were not available for the majority of the systems and so could not be used in calculations; even if they were it would be unwise to base protection ratios for planning on such results as they would then be very equipment specific. Therefore in these calculations we had no option but to use the theoretical filter shapes. The good agreement between theory and calculation with co-channel interference and the agreement in the shape of the curves as the offset frequency is increased indicates that the receive filter bandwidths are close to ideal.

The out-of-band rejection of practical filters is not infinite. The rejection required for microwave link equipment is specified. However the approach used is that, in the absence of noise, a given level of CW interference must not result in a BER of worse than a given threshold. This requirement applies to the entire link receiver over a range of frequencies excluding those adjacent to the wanted channel. It is difficult to deduce the receive filter rejection from this specification as it depends on a number of parameters of the overall receiver. A second check is specified to check the effects of interference from a similar system at one spot-frequency offset. This check does not allow a unique out-of-band filter rejection to be deduced. Therefore, whilst checks related to the receive filter out-of-band rejection are specified, the actual rejection is not specified and can not be easily or uniquely determined.

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* *The correction factor is also a function of the implementation margin.* In the calculations, implementation margins of 1 dB and 2 dB were used. The difference in the correction factors was less than 0.1 dB and hence is ignored in this case.

The levels of spurious and other out-of-band frequency components are controlled by transmit spectrum masks which must be met in acceptance tests performed by the RA. These spectrum masks can be used in our calculation to determine protection ratios as they represent the worst-case out-of-band interference permitted. It is still possible for equipment to produce higher levels of interference (as was seen on the tests where one of the pieces of equipment produced higher than the permitted level of spurious output at one frequency) as it is the type design which is approved after testing of one sample piece of equipment. Nevertheless, this is still effectively a worst case as equipment will not produce energy at every frequency to completely fill the mask — if it did it would have an infinite output power!

Comparison between measured results and those calculated using the spectrum mask for the interference can now be considered. Fig. 8 shows the measured and calculated results for interference from 34 Mbit/s QPSK equipment into 140 Mbit/s 64-QAM equipment. It can be seen that the mask calculation gives the same answer as the other results at small offset frequencies. At large offset frequencies the effect of the shoulders on the mask and floor can be seen. The mask result is more conservative than the measured results as we would expect.

8.3.2 Comparison of results over the combinations of wanted and interfering signals

Having explained the general features of the results produced by the three methods we can now examine the full set of results for 1 dB degradation in *C/N* at a BER threshold of 1×10^{-6}. These results are detailed in Appendix 4 (Table A4.1 and Figs. A4.1 to A4.13). As has been noted in Sections 6 and 7, results could not be produced for every combination of wanted and interferer by all three methods; Appendix 4 therefore starts by summarising the results available for each case.

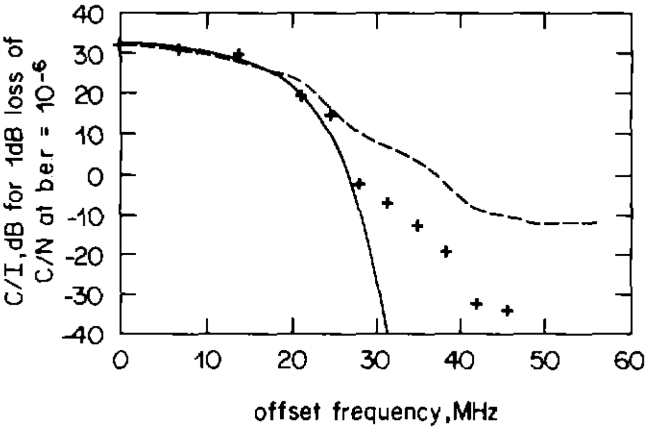

Fig. 8 - Measured and calculated results for threshold BER of 1×10^{-6}

Victim: 140 Mbit/s 64-QAM
Interferer: 34 Mbit/s QPSK
——— Calculations based on an ideal system
+ Measured results
- - - - - Calculations based on 'worst case' system masks

Considering the cases with 140 Mbit/s 64-QAM equipment as a victim (given in Figs. A4.1 and A4.2), the results continue to show good agreement. It can be seen that a co-channel *C/I* of approximately 32 dB is required when the interference is due to a like modulation system. The most significant deviation between the measured and calculated results occurs at offset frequencies between 20 MHz and 25 MHz with the relatively narrowband interferers. In these cases the measured results are approximately 10 dB higher than might be expected, it might be postulated that this was due to an imperfection in the receive filtering. This discrepancy is not serious and in general the measured results lie between the two sets of calculated results.

The results with the 140 Mbit/s 16-QAM equipment as the wanted signal follow the expected pattern (given in Figs. A4.3 and A4.4). These results show that a co-channel *C/I* of approximately 28 dB is required when interfered to by a like modulation system. The improvement over the 64-QAM equipment results from the use of fewer phase states in the modulation system.

In the cases where the 140 Mbit/s QPSK equipment was used as a victim (given in Figs. A4.5 and A4.6), the measured results sometimes showed large errors compared with the calculated figures. An example is the results with the 140 Mbit/s 64-QAM interferer where the system is between 5 dB and 10 dB more sensitive than theory would predict. The measured results clearly are doubtful as a co-channel

C/I of around 20 dB is expected for interference between QPSK systems operating at the same data rate. Values in this region have been consistently calculated and measured for the other QPSK systems. Therefore there is considerable doubt concerning this set of measurements. With the 140 Mbit/s 16-QAM and 8 Mbit/s QPSK interferers the co-channel measured results show good agreement. In the former case there is still a scatter to the results with the measurement at 42 MHz offset showing a large error.

The cases where the 34 Mbit/s QPSK equipment was used as the victim (given in Figs. A4.7 and A4.8) also show good agreement between measured and calculated results. The expected co-channel *C/I* of around 20 dB is measured. In the case using 8 Mbit/s QPSK as an interferer, the measured and calculated curves do not roll-off at the same frequency. At present we have no obvious explanation for this difference.

The cases where the 8 Mbit/s QPSK and 2 + 2 Mbit/s MSK were used as victims (given in Figs. A4.9 to A4.12) show the expected agreement between the measured and calculated values.

In all these cases, the calculations were performed for each combination of victim and interferer, allowing results to be obtained for the combinations that were not measured. Having seen good agreement between calculated and measured results there is no reason to suppose that these calculated results would not be equally accurate. These calculated results can then be compared with other measurements which form the basis for existing protection ratios.

The calculations were also performed for the analogue video interferers using the spectrum masks. As would be expected, the calculated results did not match the measured results as closely as those for the digital interferers, however they did show surprisingly good agreement. This was probably because the receive filters of the wanted systems were relatively wide and so the exact frequencies and amplitudes of the components in the analogue interference were not critical. The effect of analogue interference into all the digital systems has been calculated; however the results for the cases where the victim is a narrower-band system should be treated with more caution as the practical results are likely to be much more sensitive to the exact frequency components in the interference. In other words, the results are likely to be more sensitive to the video (and other) signals used.

The calculations were also performed for the 300-channel FDM system as an interferer. In this case, no spectrum mask was available and so only a theoretical calculation could be performed. However as the theoretical spectrum shape was not available, this was actually achieved using an approximation to the actual transmitted spectrum. The results measured and calculated results are in good agreement.

As has been explained in Section 6, at the time of writing, a program for calculating the effect of interference into analogue victims has not been developed. The measured results are presented for the TV video and 3 MHz surveillance video systems (given in Fig. A4.13). Unfortunately, it was not possible to get the radar-remoting video system or the 300-channel FDM equipment working properly and so no results are available with these systems as victims.

9. DISCUSSION AND IMPLICATIONS

9.1 Discussion of results

In Section 8 results have been presented showing good agreement between measured and calculated values over a range of systems, frequency offsets and failure criteria. The expected trends have been observed: increasing tolerance to interference as the offset frequency is increased and as modulation systems with fewer phase states are used.

There is an inconsistency between the level of the mask floor and the protection ratios. It is obvious from the simple analysis in Section 8 that the difference between the *C/I* peak and floor will never be larger than the difference between the mask peak and floor. As the latter difference in most of the masks is 45 dB the *C/I* difference will never be more than 45 dB. A co-channel *C/I* of 20 dB is required for mutual protection between the QPSK systems (which have been in use for years) so in these cases the floor will not be below −25 dB. In all present planning, the channel spacing is meant to be arranged to allow an adjacent channel *C/I* of −40 dB.

The problem is to decide protection ratio curves based on these results. In any link budget the aim is to calculate the percentage of time that the link will be operational. There are three major mechanisms that can cause failure; these are noise, interference and frequency-selective fading. In practice, failure at very small percentages of time is due to a combination of these mechanisms and so the correlation between the mechanisms becomes important. Added to this is the problem of variations in performance of nominally identical equipment; this results in further statistical variations in the overall link performance. To simplify matters it is normal to set a protection ratio to cover the cases of failure due to interference. The protection ratio gives the maximum amount of interference that can be tolerated by the wanted system and still have it just working. In this case the performance criterion agreed by the RA is the *C/I* which results in a 1 dB loss of *C/N* performance at a threshold BER of 1×10^{-6}.

The protection ratios can be based either on calculations or measured results. If they are based on calculations then it is important that they use realistic parameters, however the results are reproducible and not specific to particular equipment. Such calculations must be checked by experimental measurements to provide confidence in their validity. If the protection ratios are based on measured results then their validity is not in question, however many sets of equipment must be measured exhaustively to remove experimental error and spurious results from atypical equipment. In these tests we have not made exhaustive tests on many sets of each equipment, therefore the latter approach is not possible. However the calculations have shown reasonable agreement with the measured results (given the earlier discussion of the differences) and so we have reasonable confidence in the validity of the calculations.

In either case, a problem remains in deciding whether the worst-case result or parameter is taken at every stage in the process. If this is done then the link will end up over-engineered, as every worst-case condition is highly unlikely to occur simultaneously, and the frequency spectrum will be used inefficiently. If a result or parameter is chosen which is met by a given percentage of the systems then the problem is one of determining a suitable percentage. This can be a very complicated and link-specific problem. We suggest that the best solution is to adopt the latter approach and make a value judgement about suitable parameter values.

Each of the curves discussed in Section 8 can be divided into three broad regions. The first is the co-channel region and covers frequencies from no offset to the offset where the system is, say, 5 dB more tolerant to interference than the co-channel case. In this region there is excellent agreement between the results obtained by all three methods and, because the interfering signal largely overlaps with the receive filter, it is unlikely that there would be much variation in these results over a range of receivers which use that modulation method. Therefore the protection ratio curve could reasonably follow the *C/I* curves over this region.

The second region is the roll-off region from the frequency offsets where the system is 5 dB more tolerant to interference than the co-channel case, to offsets where the results of the mask calculations reach the floor. In this region the calculated curves are different depending on the assumptions made about the interfering spectrum. In most cases the measured results fall between the two calculated curves. Some variation in measured results may be expected between practical receivers. However, as the curves have a steep slope, these differences are unlikely to result in large changes in the offset frequency required to obtain a given tolerance to interference. Therefore although there are some differences between the sets of results, it would be reasonable to plan using calculations based upon the worst-case interference-spectrum-mask results.

The final region covers the large frequency offsets. In this region the theoretical calculations suggest that infinite amounts of interference can be tolerated — this is unlikely. The interference mask calculations suggest that the equipment can only tolerate modest levels of interference at even very large offsets — this is unnecessarily pessimistic. The measured results indicate a variety of results between these extremes. These measurements were difficult to make because of the problems of maintaining linearity and preventing blocking of the low-level wanted signal by the high-level of interferer. Such measurements will also be very equipment specific. Therefore none of these results form a reliable basis for setting protection ratios.

9.2 Methods of setting protection ratios

The ideal arrangement would be for the receive filter sensitivity curves to be specified for each system and tested as part of the equipment acceptance tests. The calculations could then be performed using specified (and hence not equipment specific) receive filter and interferer spectrum masks.

The permitted spectrum masks should also be modified as the floor to the mask is very high and could not form the basis for planning, even for the existing systems. A balance is required between setting the mask too lax and making it too tight. The former does not allow frequency-efficient planning and the latter may add significantly to the cost of the equipment. In most practical cases equipment which fails to comply with the mask does so because of spectral components at one or two frequencies. The most suitable approach would be to lower the floor by 20 dB to 30 dB but allow a few spurious outputs up to 20 dB above this floor, providing the total out-of-band power was less than say 0.001% of the total. The numbers in this case indicate appropriate levels but are by way of an example only. This overall approach would give the most reliable and consistent protection ratio.

It should be noted using this approach that if suitable floors are not chosen for the receive filter and interfering spectrum masks then the protection ratio results might never be consistent with existing planning practice. That is, if too high floors are chosen then the protection ratio results would not allow a C/I of -40 dB at any offset. This would disagree with planning practice which has been used for years where links are permitted over the same path providing there is adequate frequency separation.

A practical problem is that an extra measurement would be required as part of the acceptance test. This might not be easy to perform for some equipment.

An alternative approach is to use the existing calculations and measurements. None of the results for large frequency offsets are suitable for use directly, therefore a suitable compromise should be used. The approach we suggest is to use the calculations for frequency offsets between zero and the point where the system is 20 dB more tolerant to interference than the co-channel case. A straight line is then used between this point and a point 50 dB lower at twice the frequency offset. The line can be continued at this slope to the -40 dB point for the 64-QAM system. The approach is purely arbitrary, but gives a reasonable protection ratio curve which should give good results under most conditions. The protection ratio curves using this algorithm for interference into the 140 Mbit/s 64-QAM system by 34 Mbit/s QPSK, 8 Mbit/s QPSK and TV video FM are shown in Figs. 9, 10 and 11 respectively.

In this second case, it would appear that some of the systems tested are more sensitive to interference at odd frequencies than these proposed protection ratio curves. This is not a significant problem as a few measured results are not statistically significant, particularly in view of the difficulties in making reliable measurements at large negative values of C/I. In any case the exact shape of the protection ratio curve is not as important as the point on the C/I axis corresponding to the fade margin; for example, the -40 dB point on the C/I axis in the case of the 7.5 GHz private-user band. This gives the permissible adjacent channel spacing.

These approaches show that protection ratios can be set which should allow high-capacity digital links to be used in the lower-frequency, private-user bands. In general, the protection ratios for interference into the new systems will be more stringent than those for the systems in use at present; this is because higher-level modulation systems are more sensitive to interference than lower-level ones. The protection ratios for interference for the new systems into the existing systems are comparable with those for interference from existing systems with similar RF bandwidths.

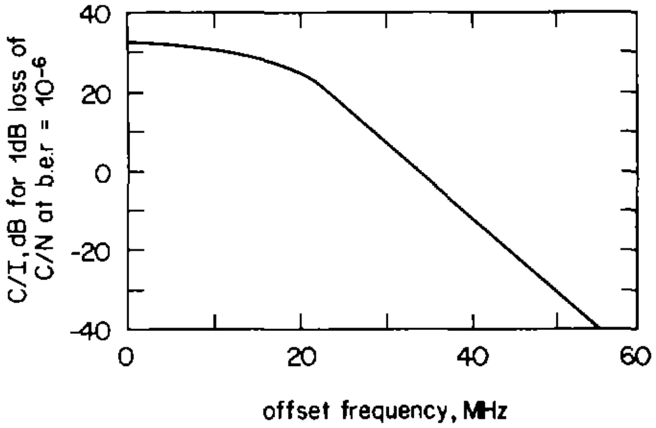

Fig. 9 - Proposed protection ratio curve.

Victim: 140 Mbit/s 64-QAM
Interferer: 34 Mbit/s QPSK

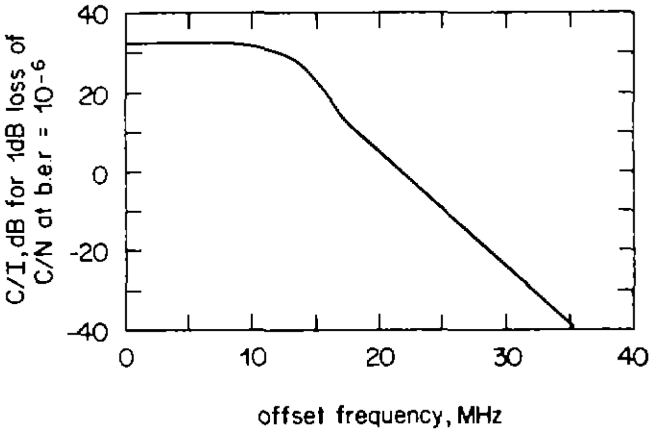

Fig. 10 - Proposed protection ratio curve.

Victim: 140 Mbit/s 64-QAM
Interferer: 8 Mbit/s QPSK

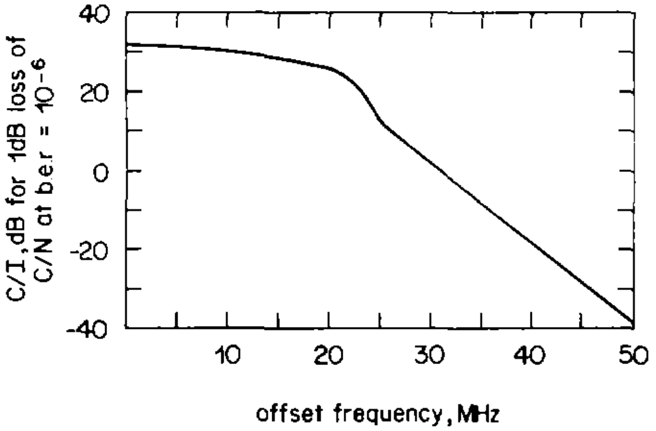

Fig. 11 - Proposed protection ratio curve.

Victim: 140 Mbit/s 64-QAM
Interferer: TV video FM

9.3 Implications for frequency assignment

Unfortunately, either of these approaches results in protection ratios for existing systems which differ somewhat from those in use at present. These differences are largely caused by differences between the methods of specifying the acceptable degradation due to interference. To achieve consistent frequency planning it is important that the same method is applied for all types of system and that this matches the assumptions used in the propagation prediction model. Some allowance for worst-case planning will then be built-in because equipment will usually perform better than the specification demands.

The COST 210 Project will provide more up-to-date and accurate propagation information collected specifically for interference studies. It may be that some test reassessments should be undertaken using the new protection information presented here and the new propagation information.

It is worth noting that, whilst using more spectrally-efficient modulation systems should make more efficient use of the spectrum, the improvements may not be as great as was initially hoped. A more spectrally-efficient system is likely to have a higher failure *C/N* and to be more sensitive to multipath propagation and interference. As a result, the hop lengths that can be achieved (all other parameters remaining unchanged) are likely to be reduced. This may mean that a link will require more hops and so more frequencies, or less frequency re-use.

There will be a point where greater spectrum efficiency is not obtained by using more bandwidth-efficient modulation systems. This point is likely to depend on a number of parameters, such as the frequency band that is used. A detailed discussion of frequency planning methods lies outside the scope of this Report; however the results documented in this Report should allow such a study to be conducted.

10. CONCLUSIONS

A set of experimental measurements and theoretical calculations has been performed to determine the levels of interference that can be tolerated by various dissimilar modulation systems. Both analogue and digital modulation systems have been considered.

The work determined suitable protection ratios for two digital modulation systems so that they could be used for terrestrial microwave links. The systems were a 140 Mbit/s 64-QAM system and a 140 Mbit/s 16-QAM system. A number of existing sets of QPSK and analogue FM microwave-link equipment were considered as both interferer and wanted systems. These results show that it should be practical to introduce these new systems without adversely affecting existing links.

During the course of the experimental and theoretical work a number of points were noted. In general, good agreement was found between the measured and calculated results. This was particularly true at small frequency offsets between the wanted and interfering signals. At large offsets the measured results became very equipment specific and the calculated results depended closely on the out-of-band filter and interference spectrum responses that were assumed. These are not fully specified and checked in the Radiocommunications Agency type-approval tests. In particular, it was found that if worst-case assumptions were made, then more than one link over the same path could never be allowed, whatever the frequency separation of the signals!

It was also noted during the work that a number of different methods are used to specify the amount of degradation due to interference that is acceptable.

11. RECOMMENDATIONS

It is recommended that protection ratio curves for link planning be determined by either the modified calculations or the algorithm outlined below.

Either:

a) a suitable receive filter response should be specified and checked during the type-approval tests. Also the permissible spectrum masks should be modified to reduce the level of the out-of-band floor; calculations would then be performed with these more representative masks to produce protection ratio curves.

Or

b) a new algorithm is proposed for producing protection ratio curves from the calculated results. The algorithm consists of using the calculated results using the interference spectrum masks up to a frequency offset where the system is 20 dB more tolerant to interference than the co-channel case. A straight line is then used between this point and one 50 dB lower at twice the frequency offset. It is thought that this curve will give acceptable results.

This approach should be used both for links using the new modulation systems and for new links involving existing QPSK or analogue FM equipment. It is also important to ensure that the approach used is consistent with the assumptions made in the propagation model.

12. ACKNOWLEDGEMENTS

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British Gas plc
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Ferranti Industrial Electronics Ltd
GEC Plessey Telecommunications Ltd
Independent Broadcasting Authority
Macom Ltd
Mercury Communications Ltd
NEC (UK) Ltd

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We would like to thank P.R. Durrant, G. Robertson and A. King for their help in performing the experimental measurements.

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APPENDIX 1

System Parameters and Interference Masks used in Theoretical Calculations

The parameters used in the theoretical calculations are shown in Table A1.1.

Table A1.1: Parameters used in theoretical calculations

System	Correlation states (M)	Info rate (Mbits)	FEC rate	CRO factor	Implementation margin (dB)
140 Mbit/s 64-QAM	64	140	81/84	0.3	1
140 Mbit/s 16-QAM	16	140	1	0.6	2
140 Mbit/s QPSK	4	140	1	1.0	1
34 Mbit/s QPSK	4	34	1	0.7	1
8 Mbit/s QPSK	4	8	1	0.4	1
2 + 2 Mbit/s MSK	4	6	1	1.0	1

In case of MSK this is an approximation which equates the spectral width of the signal to that of an equivalent QPSK signal with a higher data rate.

Transmit spectrum masks are used for type approval of equipment by the Radiocommunications Agency. These masks represent the worst-case transmit spectrum that should occur in practice. A series of such masks is illustrated in Figs. A1.1 to A1.7.

Figs. A1.1 to A1.4 show the masks for the QPSK and MSK systems. At the time of writing, no agreed masks exist at present for the 16-QAM and 64-QAM systems. Figs. A1.5 and A1.6 show proposed masks for narrowband video, and broadcast and radar-remoting video respectively.

No mask is available for the 300-channel FDM system. The transmit spectrum was difficult to describe mathematically so a piecewise-linear approximation was generated and used in a mask calculation. Fig. A1.7 shows the approximation that was used; the result is effectively an approximation to the theoretical result as the approximation is not a worst-case mask.

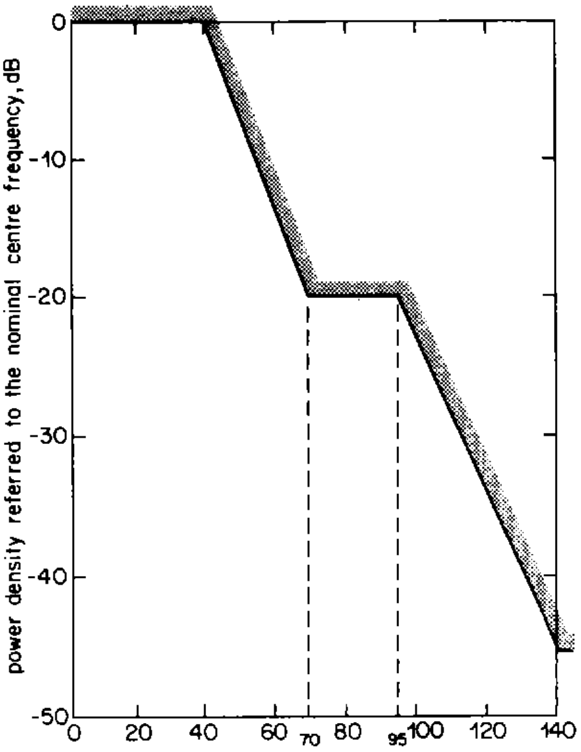


Fig. A1.1 - 140 Mbit/s QPSK spectrum mask.

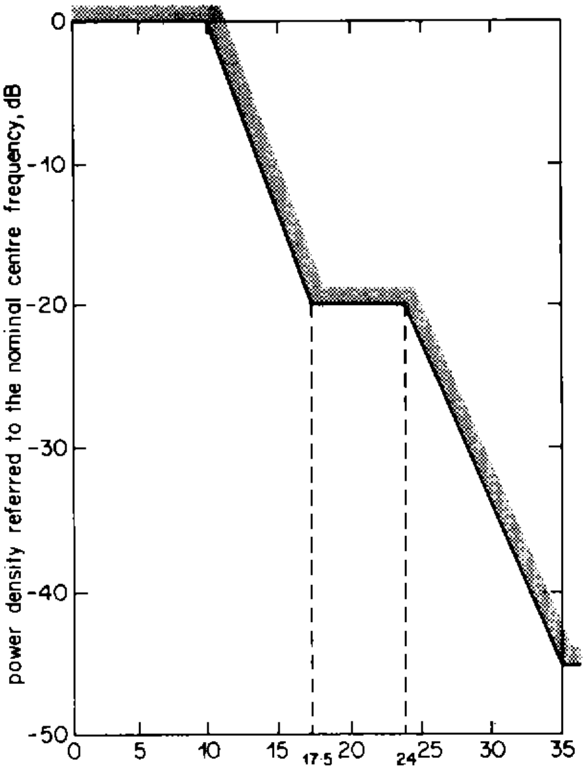


Fig. A1.2 - 34 Mbit/s QPSK spectrum mask.

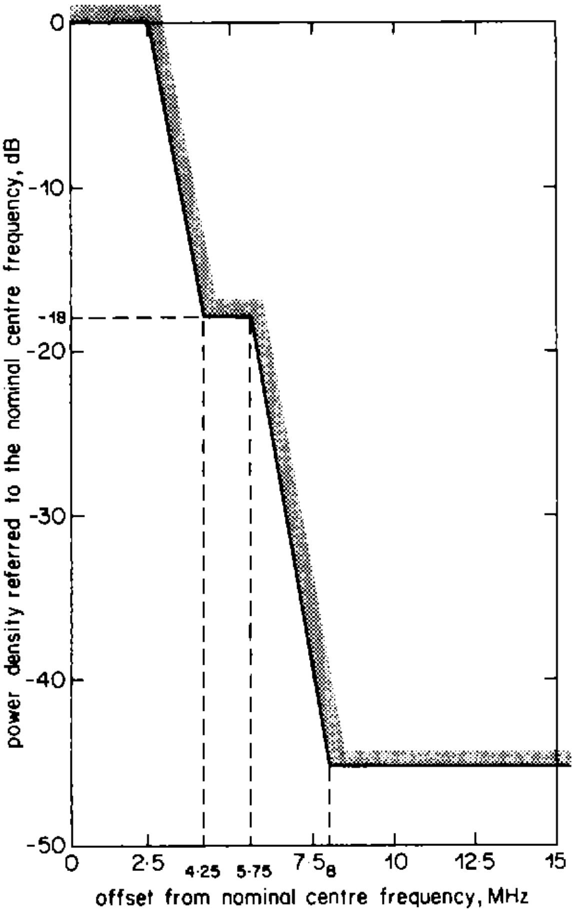


Fig. A1.3 - 8 Mbit/s QPSK spectrum mask.

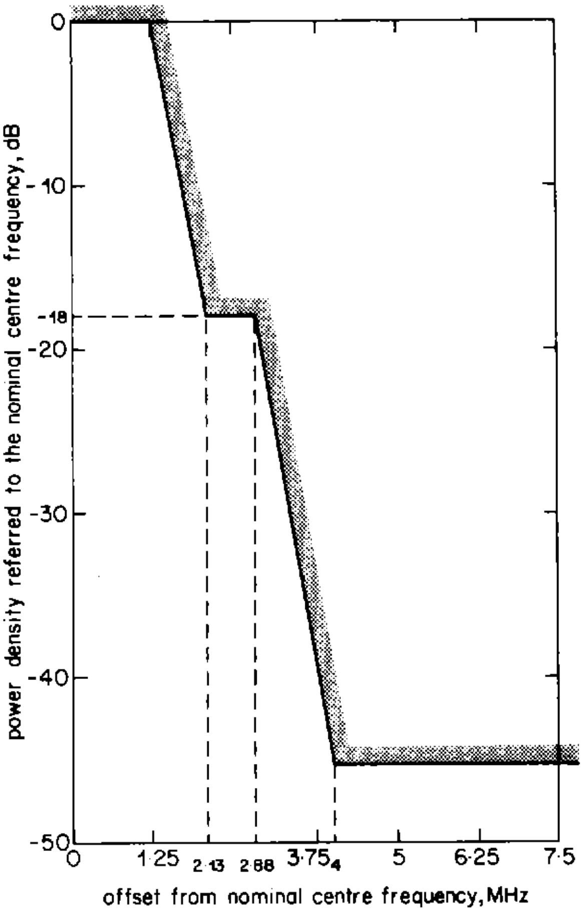


Fig. A1.4 - 2 + 2 Mbit/s MSK spectrum mask.

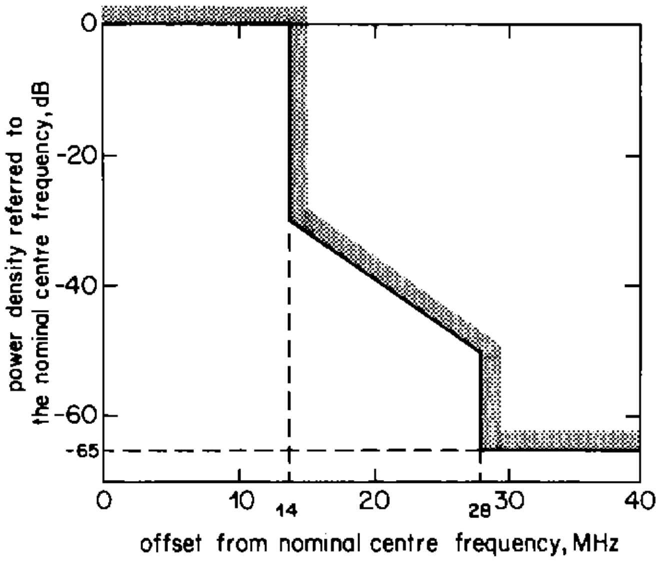


Fig. A1.5 - Narrowband TV spectrum mask.

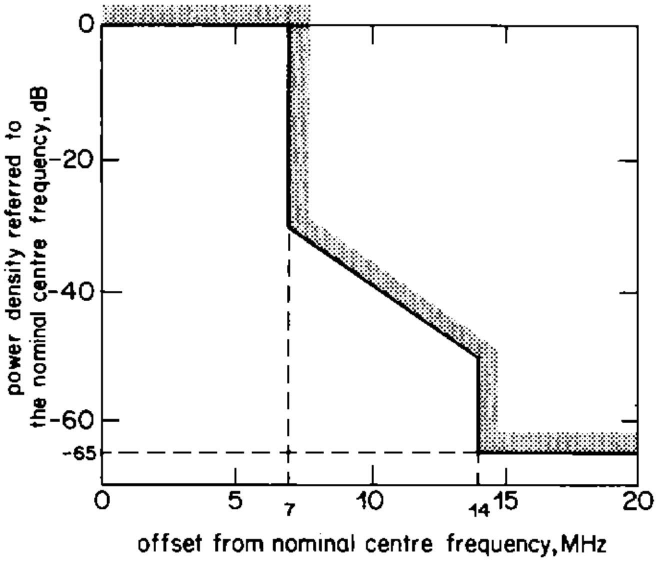


Fig. A1.6 - Broadcast TV and wideband radar-remoting video spectrum mask.

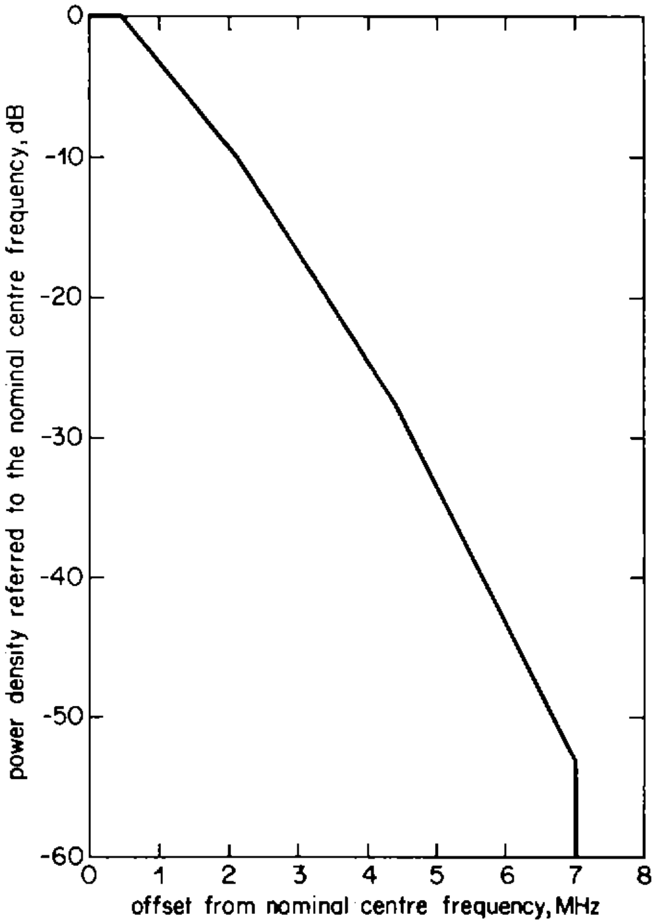


Fig. A1.7 - Interfering spectrum used for 300-channel FDM calculation.

APPENDIX 2

Equipment Details and Typical Performance

1. 140 Mbit/s 64-QAM

Manufacturer	NEC
Type	Model 700 Series
Frequency	14.5 to 15.35 GHz
Channel Spacing	28 MHz cross-polar, 56 MHz co-polar
Roll-off Factor	0.3

Transmitter

Configuration	Dual TWT amplifiers
Power Output	+35.5 dB modulated (branching filter input) +27.3 dB unmodulated (branching filter input)

Receiver

Configuration	Space diversity with IF combiner
Noise Figure	3.3 dB at 15 GHz (branching filter output)
Nominal Receiver Input	−34 dB
Receiver Input Level	
for 1×10^{-4} BER	−69.5 dB ($C/N = 25$ dB)
for 1×10^{-6} BER	−67 dB ($C/N = 27.5$ dB)
Receiver Noise Bandwidth	24.76 MHz

2. 140 Mbit/s 16-QAM

Manufacturer	GPT
Type	Development model
Frequency	6.430 - 7.110 GHz (CCIR Rec. 384-4)
Channel Spacing	40 MHz cross-polar, 80 MHz co-polar
Roll-off Factor	0.5

Transmitter

Power Output	+29.3 dBm (modulated) +31.4 dBm (unmodulated)

Receiver

Noise Figure	3.5 dB
Receiver Input Level	
for 1×10^{-4} BER	−75 dBm
for 1×10^{-6} BER	−72.5 dBm

3. 140 Mbit/s QPSK

Manufacturer	Ferranti
Type	24000
Frequency	17.7 - 19.7 GHz (CCIR Rec. 595)
Channel Spacing	110 MHz cross-polar, 220 MHz co-polar

Transmitter

Power Output	+27 dBm

Receiver

Receiver Signal Level for 1 × 10^{-3} BER	−74 dBm

4. 34 Mbit/s QPSK

Manufacturer	NEC
Type	Model 500 Series
Frequency	12.75 - 13.25 GHz (CCIR Rec. 497-2)
Channel Spacing	28 MHz cross-polar, 56 MHz co-polar

Transmitter

Configuration	Dual transmitters in hot-standby
Power Output	+37.5 dBm (modulated) +37.4 dBm (unmodulated)

Receiver

Configuration	Space diversity with IF combiner
Receiver Signal Level for 1 × 10^{-6} BER	−79.5 dBm

5. 8 Mbit/s QPSK

Manufacturer	NEC
Type	Model 770 Series
Frequency	7.425 - 7.725 GHz (CCIR Rec. 385-3)
Channel Spacing	3.5 MHz cross-polar, 7 MHz co-polar

Transmitter

Configuration	Dual transmitters in hot-standby
Power Output	+32.3 dBm (modulated) +31.9 dBm (unmodulated)

Receiver

Configuration	Single receiver (no diversity)
Receiver Signal Level for 2 × 10^{-5} BER	−88.5 dBm

6. 2 + 2 Mbit/s MSK

Manufacturer	DMC (Digital Microwave Corporation)
Type	DMC 13M
Frequency	12.75 - 13.25 GHz
Channel Spacing	3.5 MHz (cross-polar and co-polar)

Transmitter

Configuration	Single-ended
Power Output	+11 dBm

Receiver

Configuration	Single receiver (no diversity)
Receiver Signal Level for 1 × 10^{-6} BER	−84.5 dBm

7. Wideband Video

Manufacturer	*Ferranti*
Type	Radar Demonstration Unit
Frequency	7.425 - 7.9 GHz
Description	Baseband is a multiplex of: 1 × 5.5 MHz Video 1 × 4.5 MHz Video on 10.7 MHz s/c 8 × Audio/Data + timing on 7.5 MHz s/c

8. 300-Channel FDM

Manufacturer	GEC
Type	MH2
Frequency	7.425 - 7.9 GHz
Channel Spacing	7 MHz cross-polar, 14 MHz co-polar

Transmitter

Configuration	Dual transmitters in hot-standby

Receiver

Configuration	Duplicated receivers

9. TV Video

Manufacturer	Continental Microwave Ltd.
Type	VFL70
Frequency	7.425 - 7.9 GHz
Channel Spacing	24.5 MHz cross-polar, 49 MHz co-polar

Transmitter

Configuration	Single transmitter shelf
Power Output	+30 dBm

Receiver

Configuration	Single receiver shelf
Receiver Signal Level	
for 60 dB Video S/N UW	−42 dBm
for 1 × 10^{-3} BER	−69 dBm (TFM s/c @ −20 dBc)

10. Narrowband Video

Manufacturer	MACOM Ltd.
Type	ML20700/ML20600
Frequency	1.6 GHz
Video Bandwidth	3.5 MHz
Power Output	+25 dBm

APPENDIX 3

Results of the Characterisation of Systems

This Appendix contains the results of the tests performed to characterise the digital systems. The *x*-axis scales from the two sets of tests has been adjusted so that a best-fit curve can be drawn through both sets of results. Where they are available, the guaranteed, typical and theoretical curves have been added.

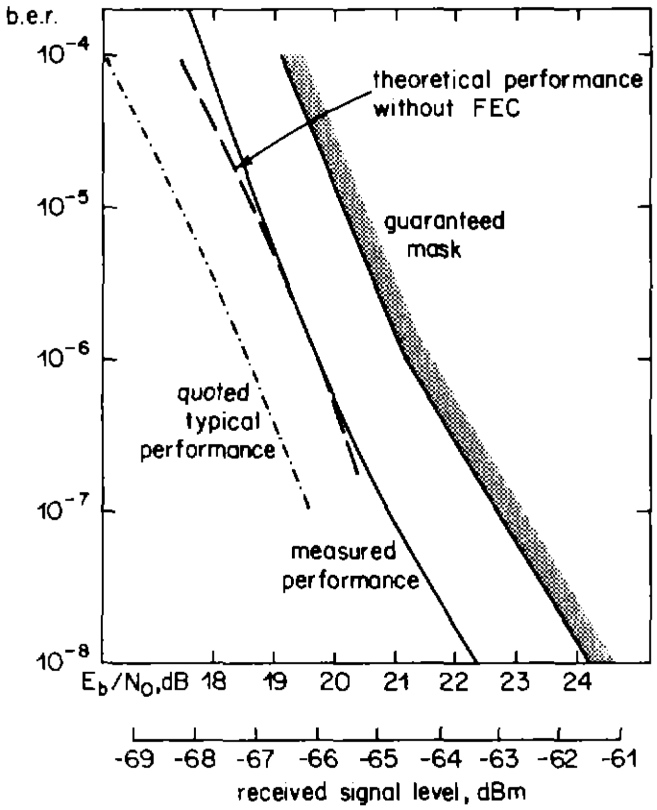


Fig. A3.1 - Performance of 140 Mbit/s 64-QAM system including FEC.

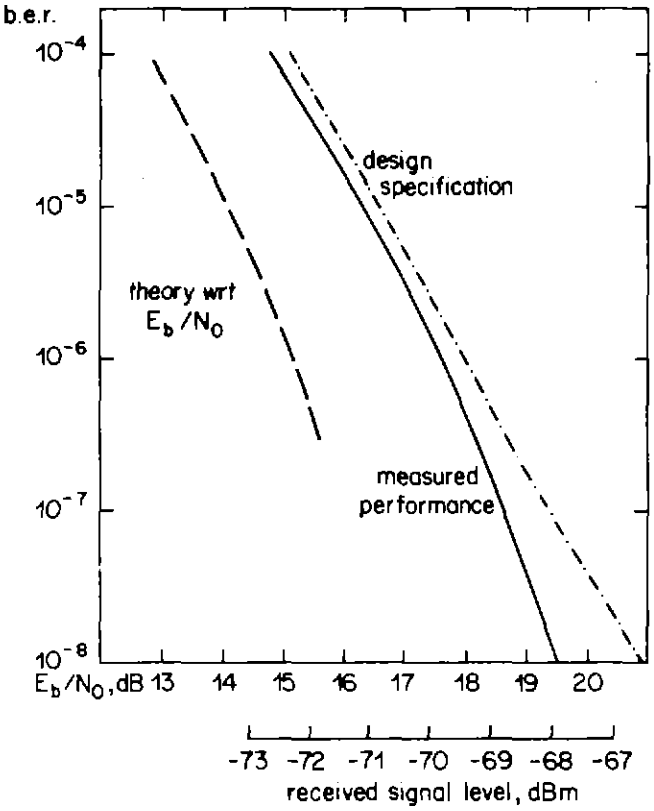


Fig. A3.2 - Performance of 140 Mbit/s 16-QAM system.

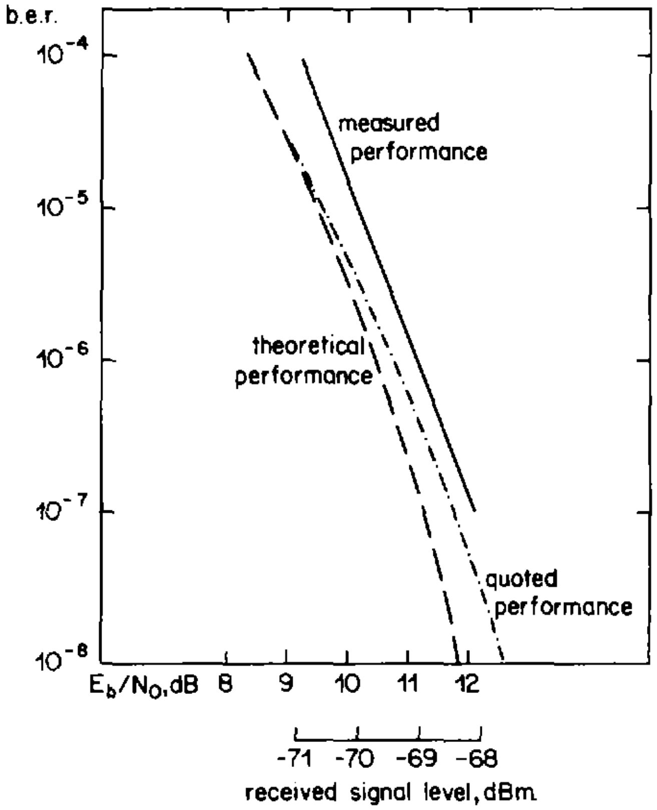


Fig. A3.3 - Performance of 140 Mbit/s QPSK system.

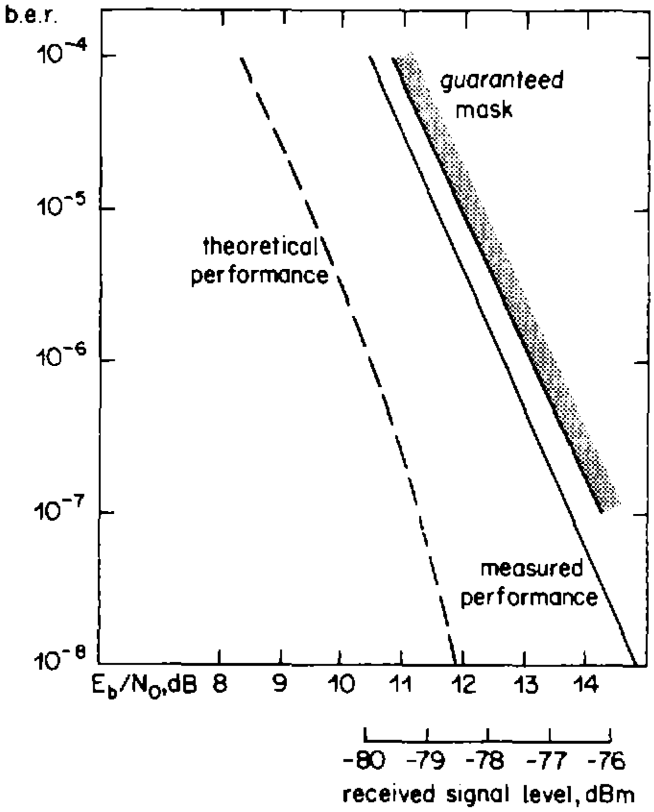


Fig. A3.4 - Performance of 34 Mbit/s QPSK system.

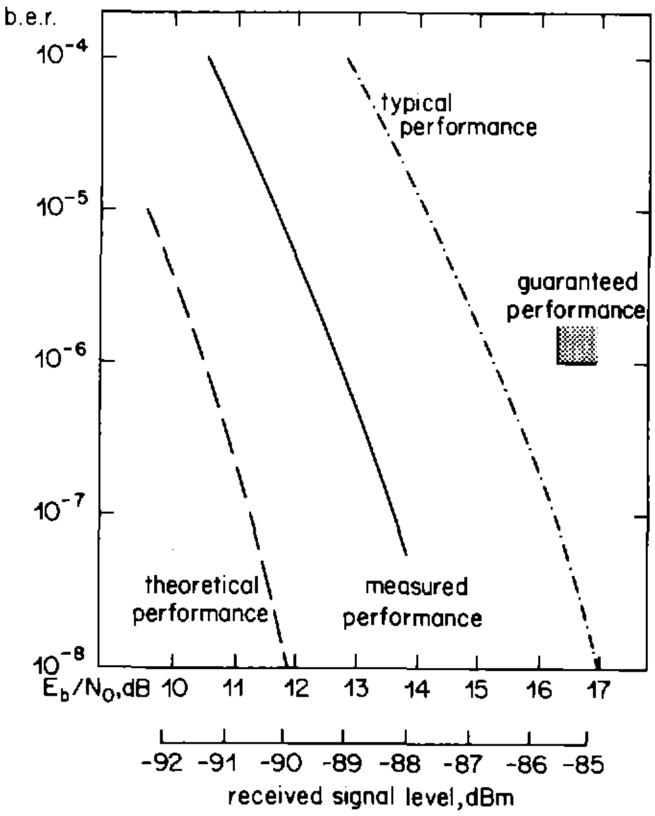


Fig. A3.5 - Performance of 8 Mbit/s QPSK system.

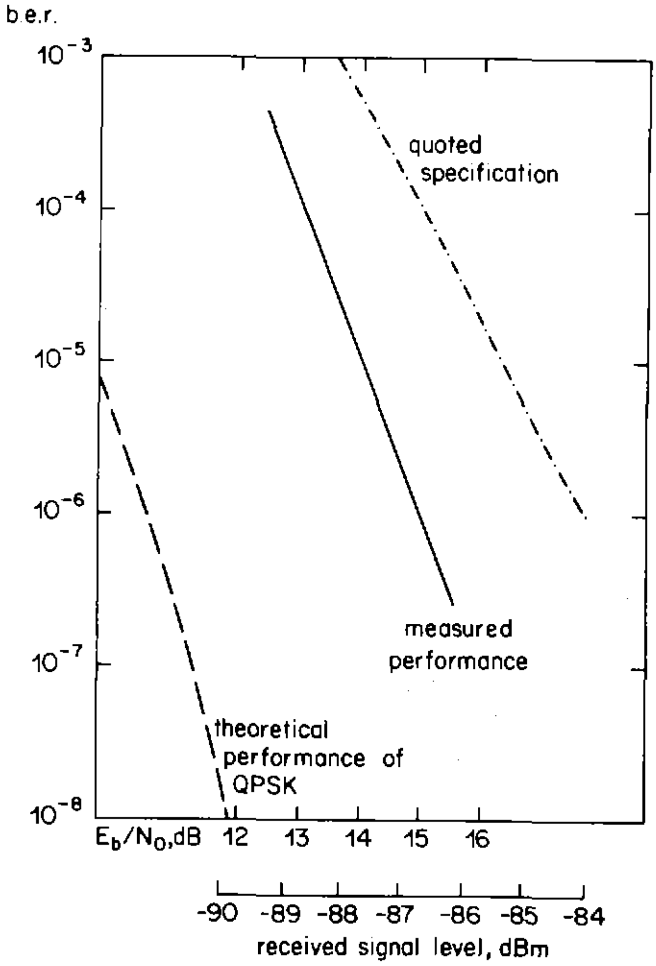


Fig. A3.6 - Performance of 2 + 2 Mbit/s MSK system.

APPENDIX 4

Graphs of Interference Results

This Appendix contains the measured and calculated interference test results in Figs. A4.1 to A4.13. The results are given for the case of 1 dB degradation in C/N at the threshold of a BER of 1×10^{-6} for the digital systems and a $S/N_{\mathrm{unweighted}}$ of 32 dB and 35 dB for the narrowband and TV video systems respectively. The threshold levels for the audio signals which accompany the TV video signal were chosen individually to be suitable levels.

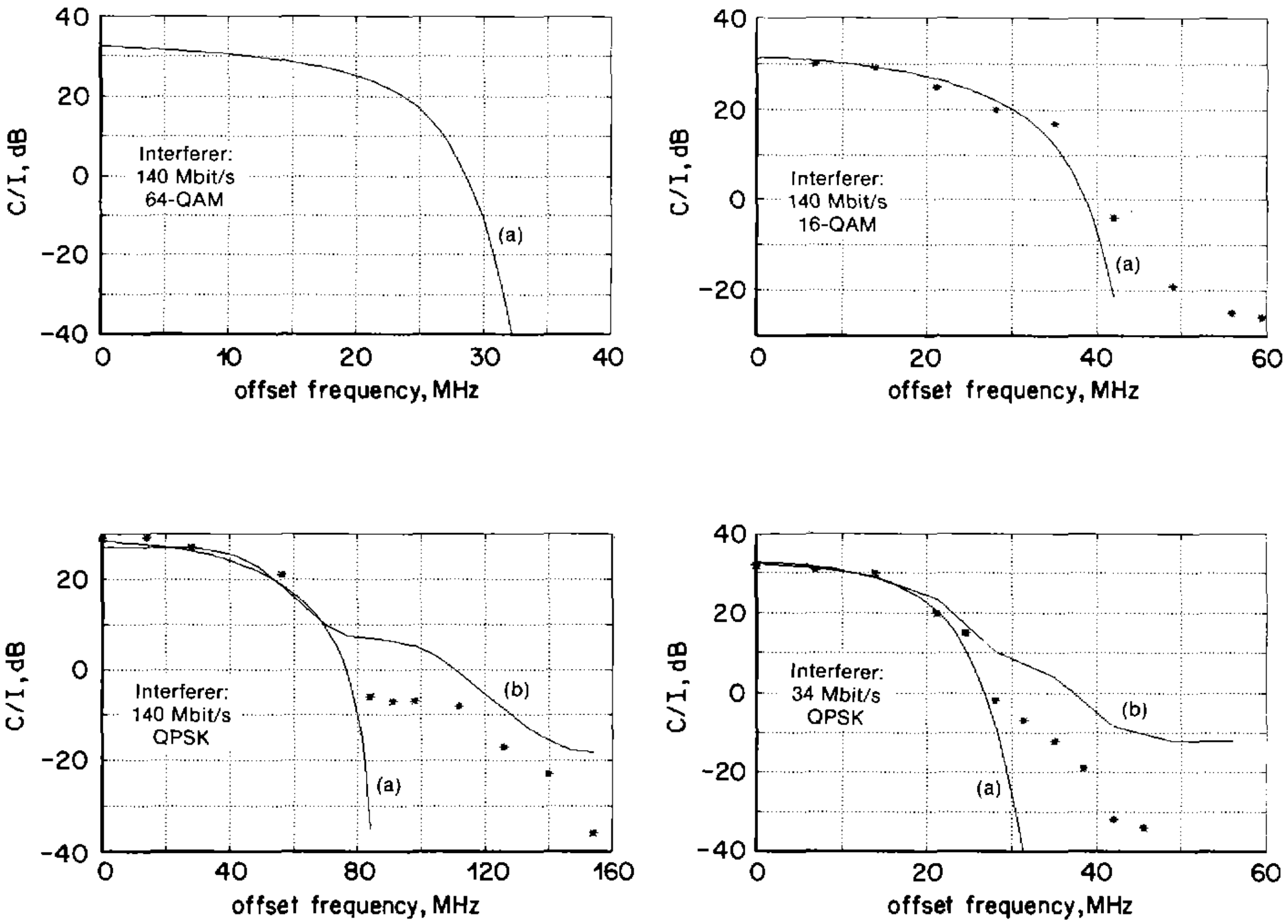
Table A4.1 shows the results that are available for each combination of victim and interferer. A full set of results was not possible for a number of reasons. Problems with the radar-remoting video and 300-channel FDM systems prevented a full set of measurements being made. The measurements concentrated on combinations involving the new systems. Difficulties in defining the spectrum for the video systems with the required picture modulation prevented theoretical interference calculations being made in these cases. Lack of agreed spectrum masks for the 140 Mbit/s 64-QAM, 140 Mbit/s 16-QAM and 300-channel FDM systems prevented spectrum mask calculations being performed with these systems as interferers.

Table A4.1: The combinations of results available

Interferers	Victim systems									
	140 Mbit/s 60-QAM	140 Mbit/s 16-QAM	140 Mbit/s QPSK	34 Mbit/s QPSK	8 Mbit/s QPSK	2 + 2 Mbit/s MSK	3 MHz video FM	TV video FM	Radar video FM	300-channel FDM
140 Mbit/s 60-QAM	T	TE	TE	TE	TE	TE	E	E	–	–
140 Mbit/s 16-QAM	TE	T	TE	TE	TE	TE	E	E	–	–
140 Mbit/s QPSK	TME	TME	TM	TM	TME	TM	–	–	–	–
34 Mbit/s QPSK	TME	TME	TM	TM	TME	TM	–	E	–	–
8 Mbit/s QPSK	TME	TME	TME	TME	TM	TM	–	–	–	–
2 + 2 Mbit/s MSK	TME	TME	TM	TM	TM	TM	–	–	–	–
3 MHz video FM	ME	ME	M	M	M	M	–	–	–	–
TV video FM	ME	ME	M	M	M	M	–	–	–	–
Radar video FM	ME	ME	M	M	M	M	–	–	–	–
300-channel FDM	TE	TE	T	T	T	T	–	–	–	–

Where:
T means calculation performed using theoretical shaped interfering spectrum
M means calculation performed using interferer spectrum mask
E means experimental measurements

Wanted signal: **140 Mbit/s 64-QAM**



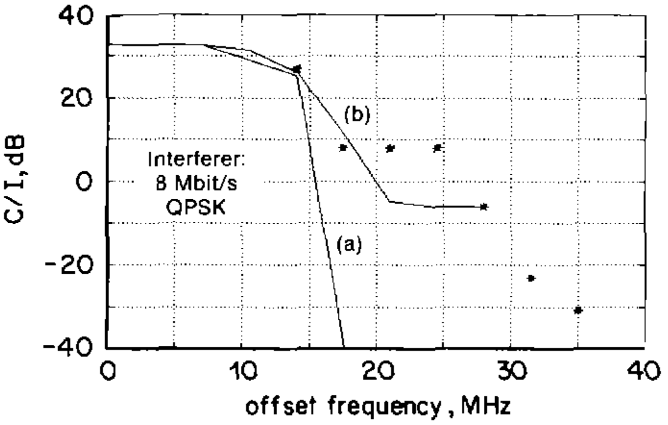
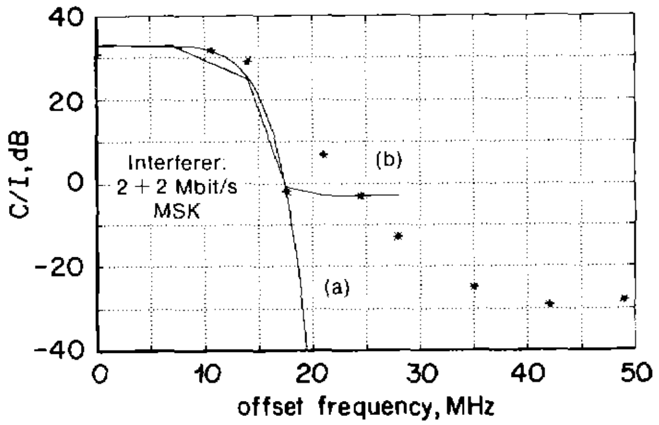


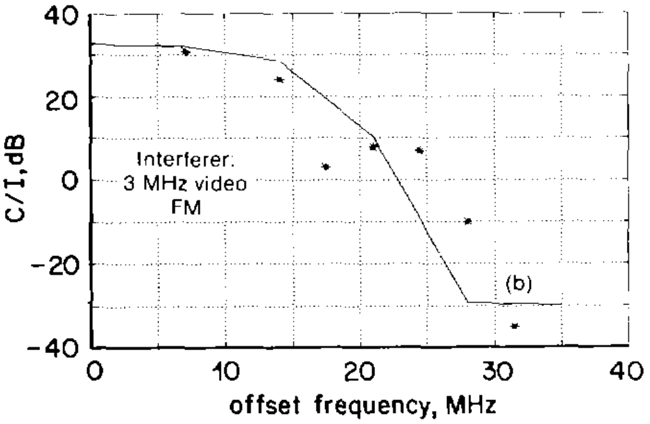
Fig. A4.1 - Calculated and measured results for 140 Mbit/s 64-QAM as the wanted system and various interfering systems.

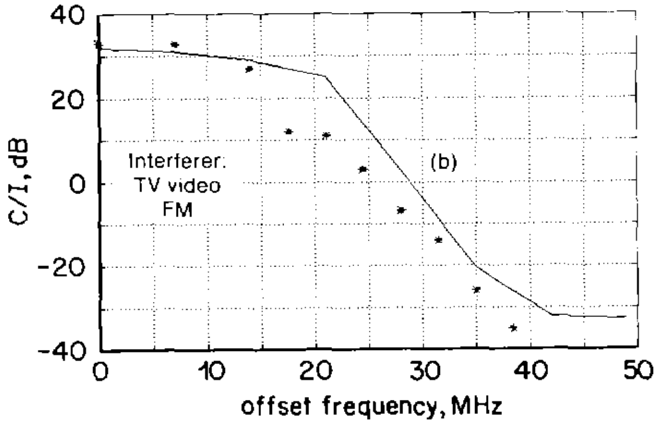
1 dB degradation in *C/N* at a BER threshold of 1 × 10^{-6}.

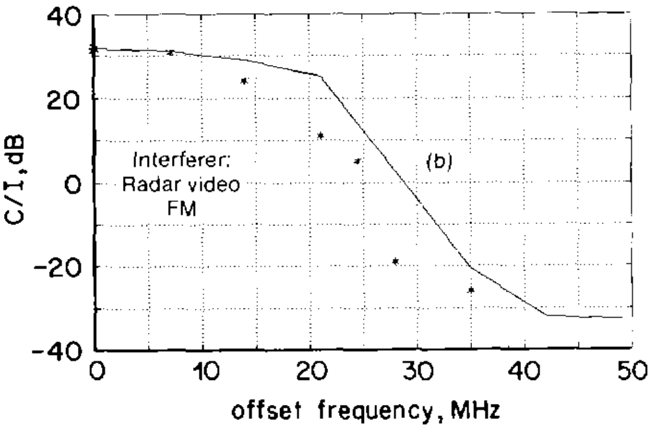
- * measured points
- (a) calculations with theoretical-shaped interfering spectrum (curve tends to infinite isolation at large offset frequencies)
- (b) calculations performed using spectrum mask shapes (curve tends to a limiting isolation at large offset frequencies)

Wanted signal: **140 Mbit/s 64-QAM**









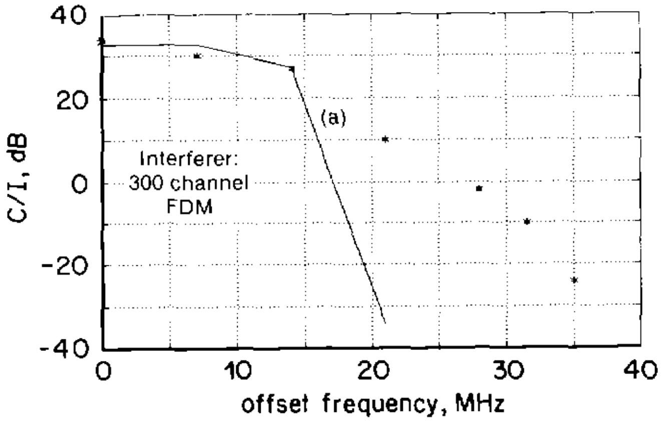


Fig. A4.2 - Calculated and measured results for 140 Mbit/s 64-QAM as the wanted system and various interfering systems.

1 dB degradation *in C/N at a BER threshold of* 1 × 10^{-5}.

- * measured points
- (a) calculations with theoretical-shaped interfering spectrum (curve tends to *infinite isolation at large offset* frequencies)
- (b) calculations performed using spectrum mask shapes (*curve tends to a limiting* isolation at large offset frequencies)

Wanted signal: **140 Mbit/s 16-QAM**

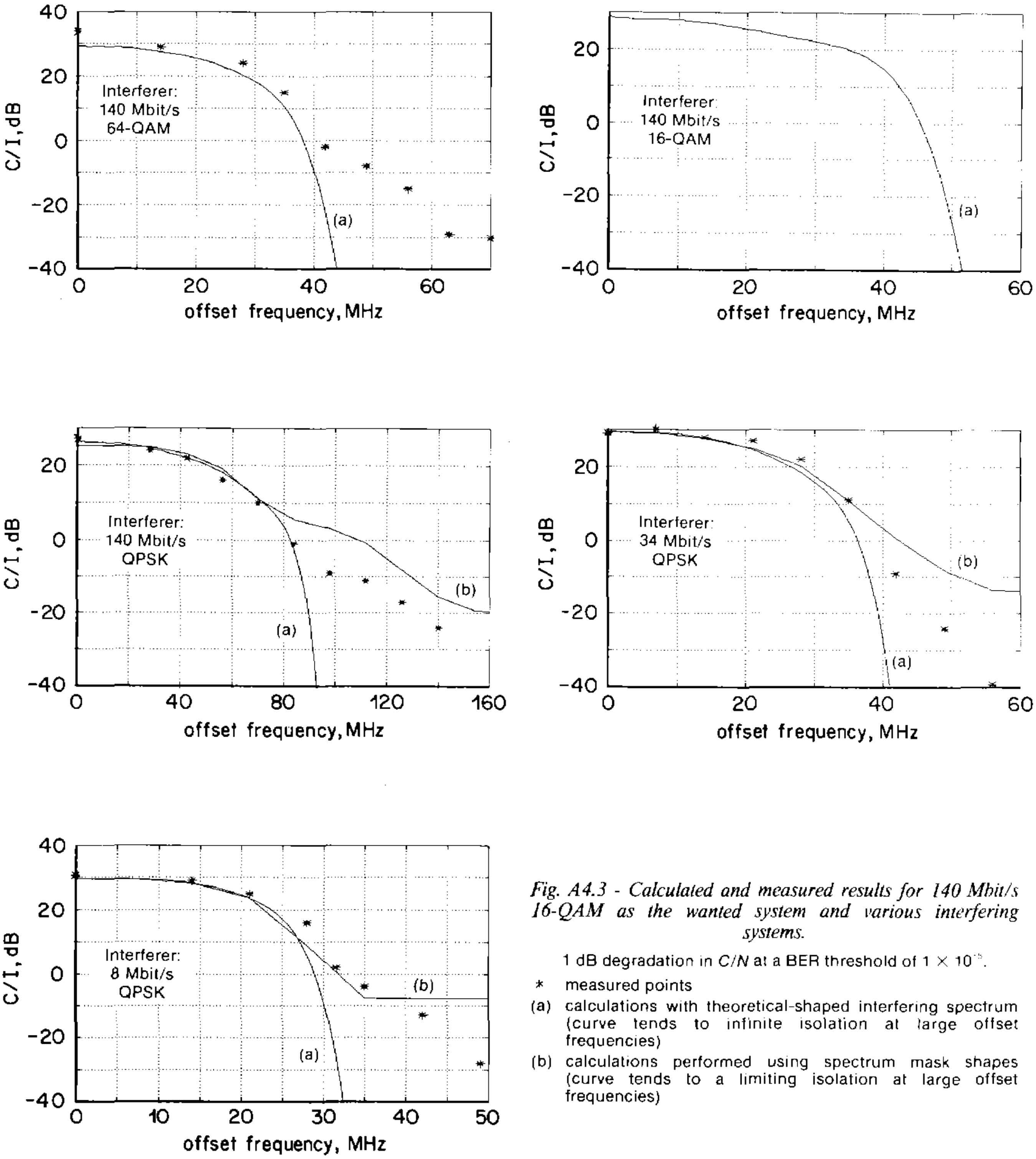


Fig. A4.3 - Calculated and measured results for 140 Mbit/s 16-QAM as the wanted system and various interfering systems.

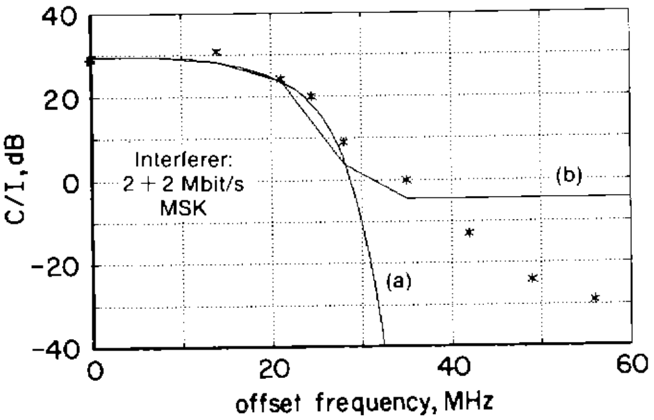
1 dB degradation in *C/N* at a BER threshold of 1×10^{-6}.

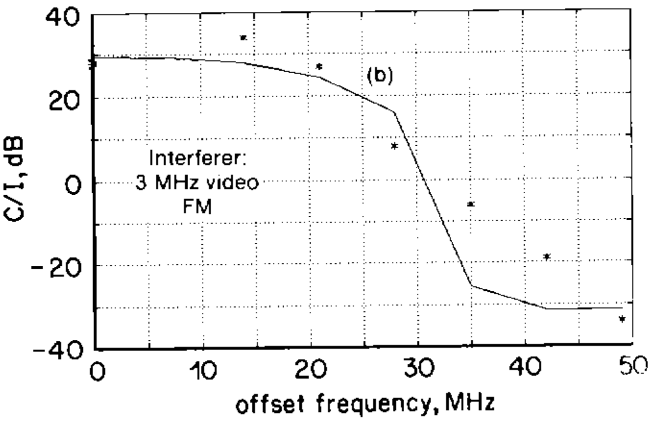
* measured points

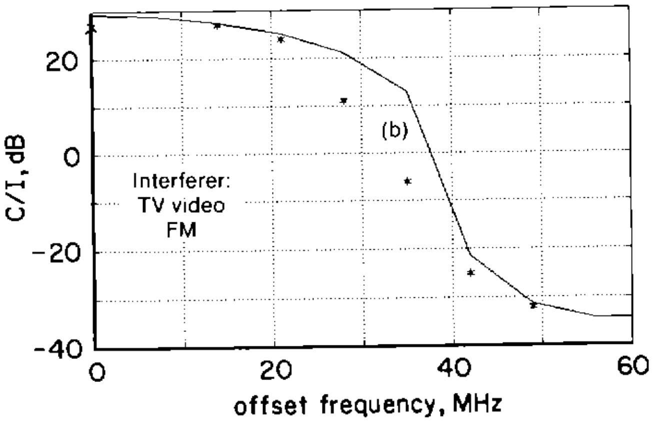
(a) calculations with theoretical-shaped interfering spectrum (curve tends to infinite isolation at large offset frequencies)

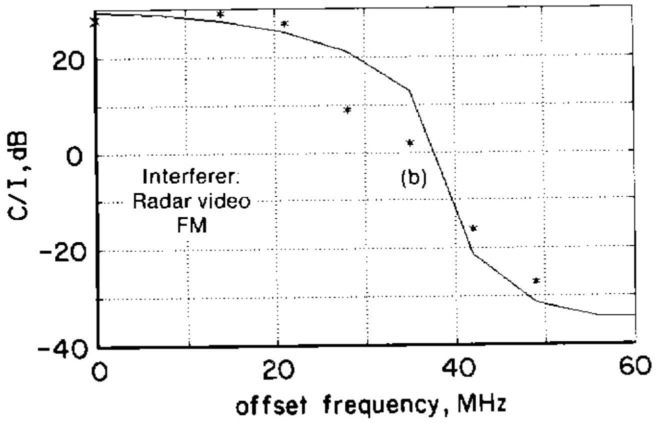
(b) calculations performed using spectrum mask shapes (curve tends to a limiting isolation at large offset frequencies)

Wanted signal: **140 Mbit/s 16-QAM**









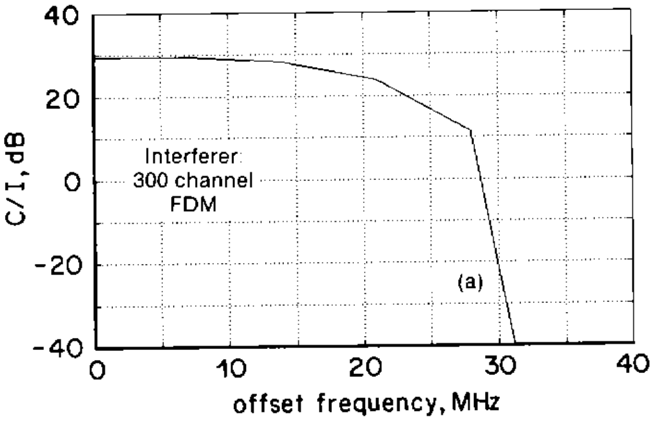


Fig. A4.4 - Calculated and measured results for 140 Mbit/s 16-QAM as the wanted system and various interfering systems.

1 dB degradation in *C/N* at a BER threshold of 1×10^{-6}.

* measured points

(a) calculations with theoretical-shaped interfering spectrum (curve tends to infinite isolation at large offset frequencies)

(b) calculations performed using spectrum mask shapes (curve tends to a limiting isolation at large offset frequencies)

Wanted signal: **140 Mbit/s QPSK**

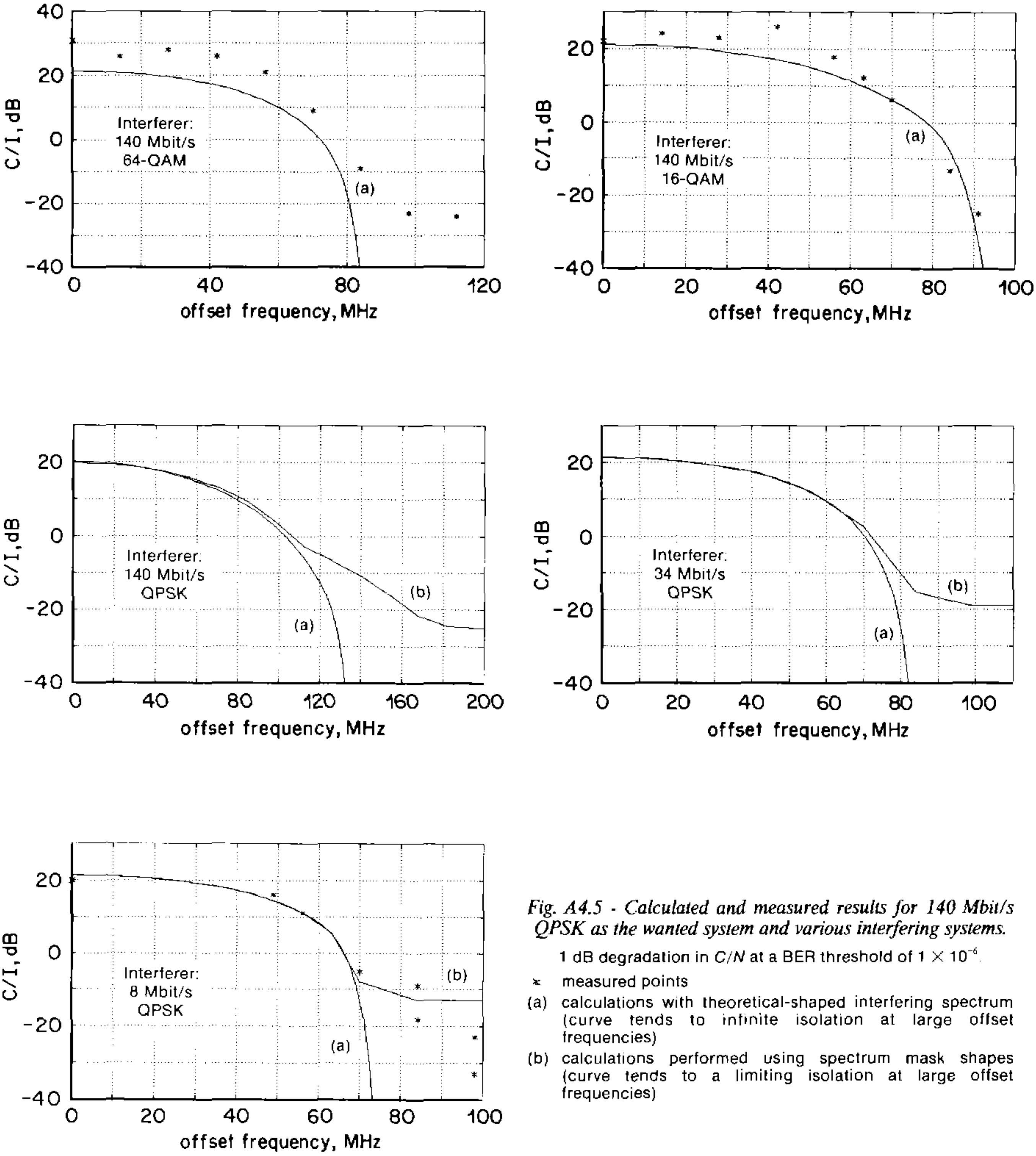
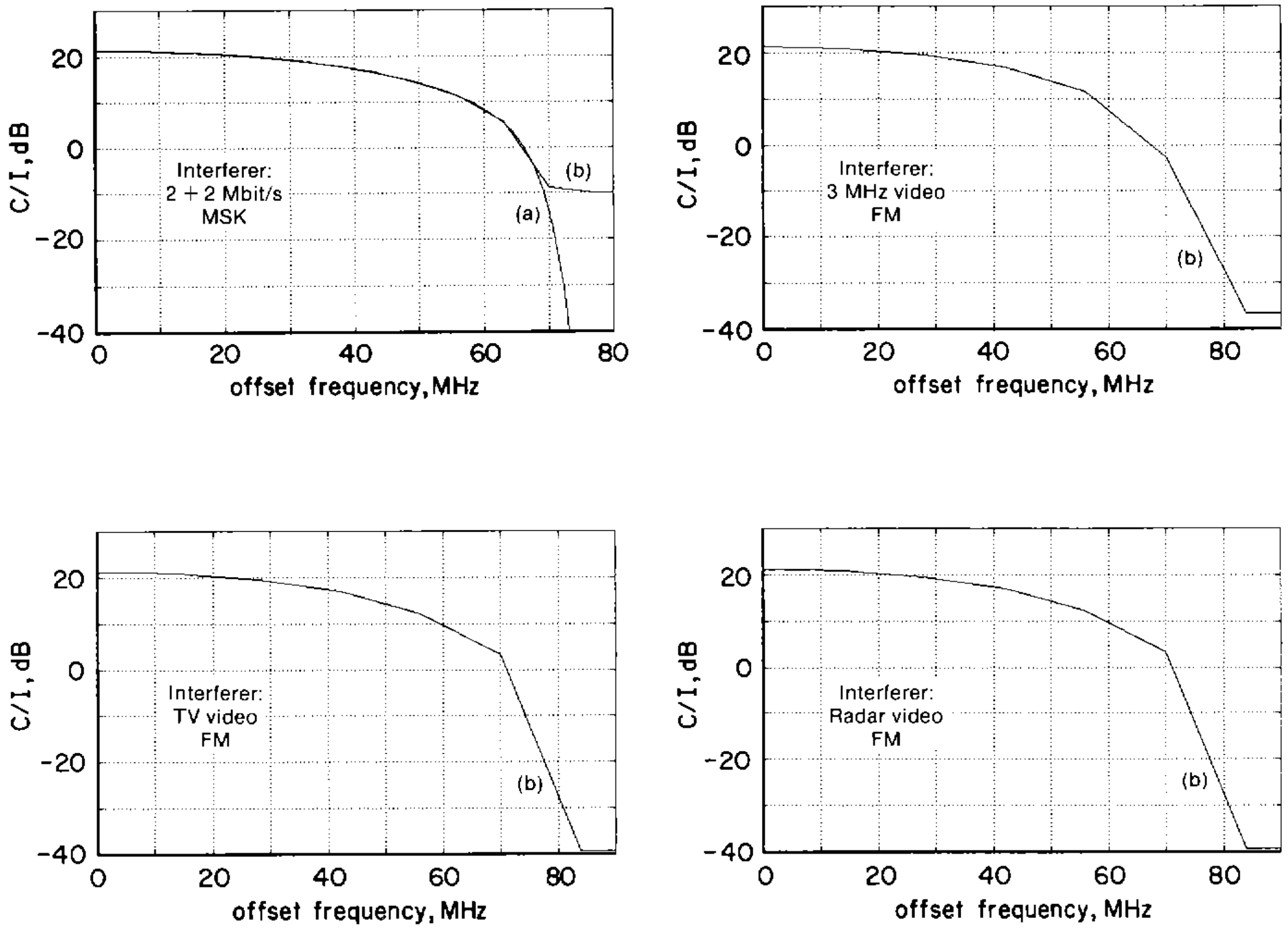


Fig. A4.5 - Calculated and measured results for 140 Mbit/s QPSK as the wanted system and various interfering systems.

1 dB degradation in *C/N* at a BER threshold of 1 × 10^{-6}.

- * measured points
- (a) calculations with theoretical-shaped interfering spectrum (curve tends to infinite isolation at large offset frequencies)
- (b) calculations performed using spectrum mask shapes (curve tends to a limiting isolation at large offset frequencies)

Wanted signal: **140 Mbit/s QPSK**



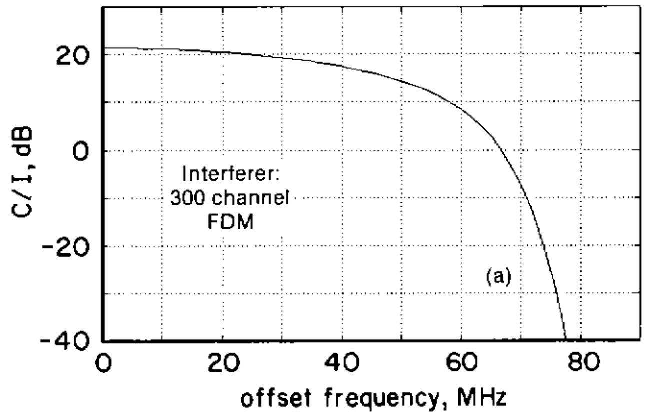


Fig. A4.6 - Calculated and measured results for 140 Mbit/s QPSK as the wanted system and various interfering systems.

1 dB degradation in C/N at a BER threshold of 1×10^{-6}.

(a) calculations with theoretical-shaped interfering spectrum (curve tends to infinite isolation at large offset frequencies)

(b) calculations performed using spectrum mask shapes (curve tends to a limiting isolation at large offset frequencies)

Wanted signal: **34 Mbit/s QPSK**

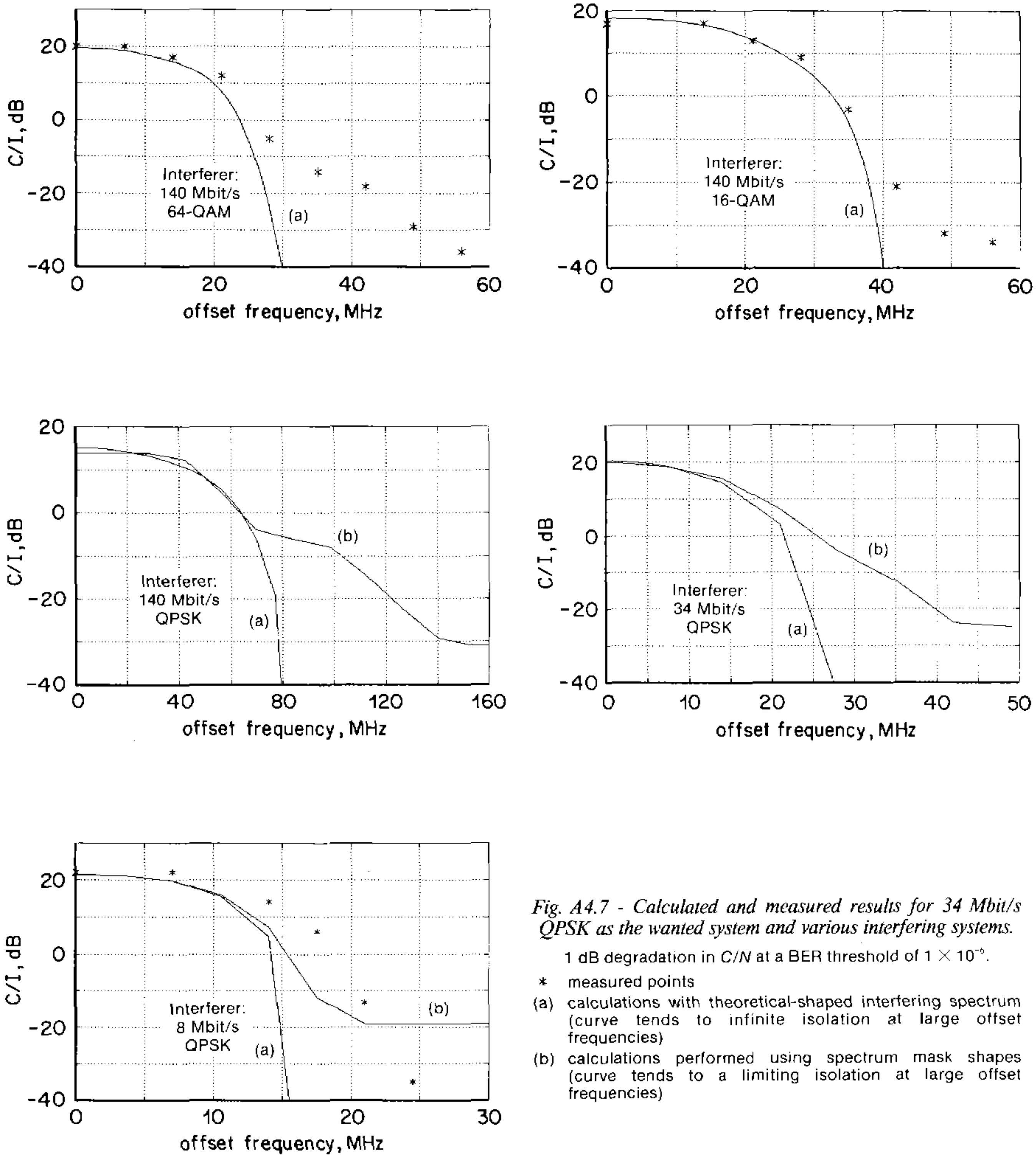
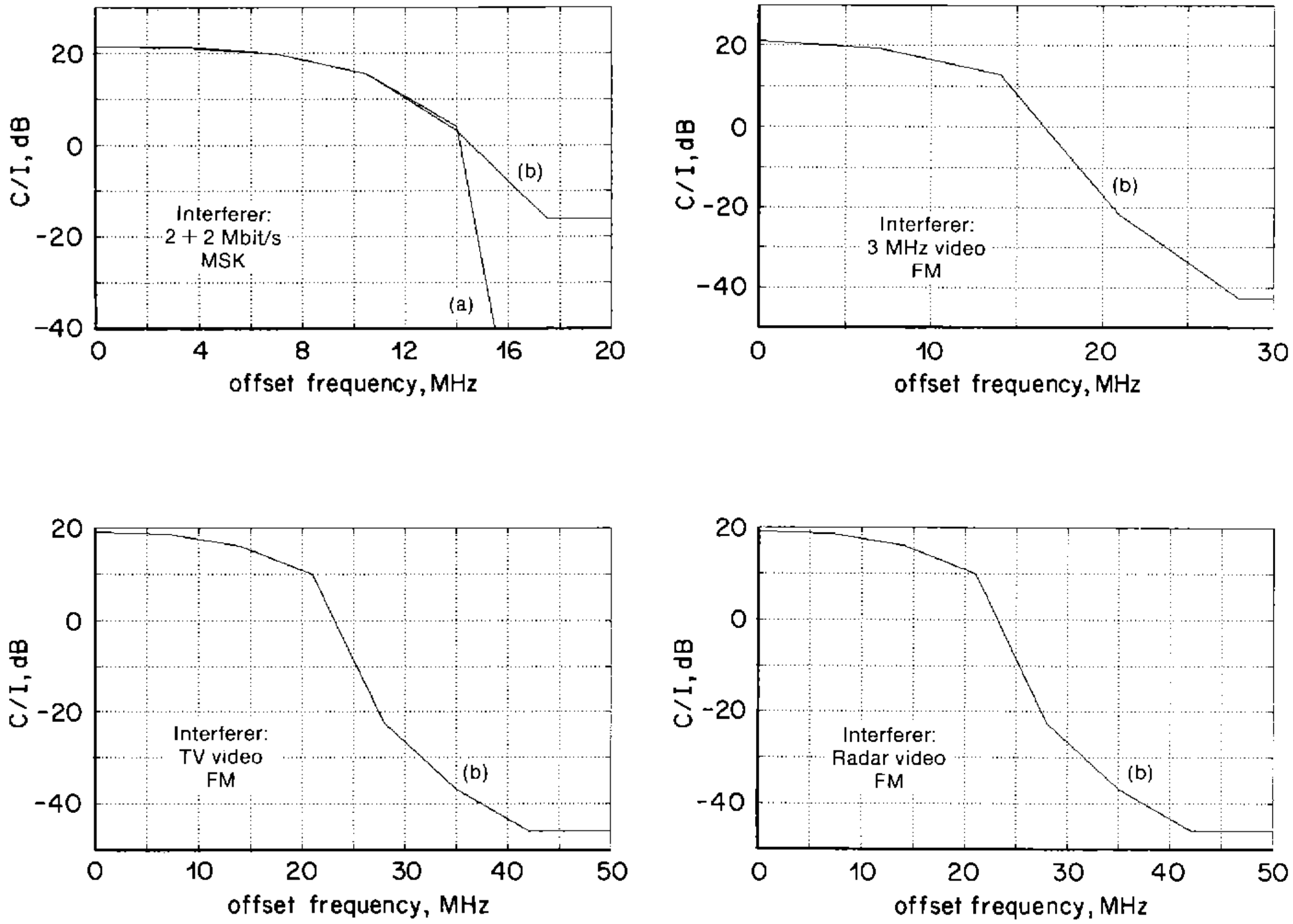


Fig. A4.7 - Calculated and measured results for 34 Mbit/s QPSK as the wanted system and various interfering systems.

1 dB degradation in *C/N* at a BER threshold of 1×10^{-6}.

- * measured points
- (a) calculations with theoretical-shaped interfering spectrum (curve tends to infinite isolation at large offset frequencies)
- (b) calculations performed using spectrum mask shapes (curve tends to a limiting isolation at large offset frequencies)

Wanted signal: **34 Mbit/s QPSK**



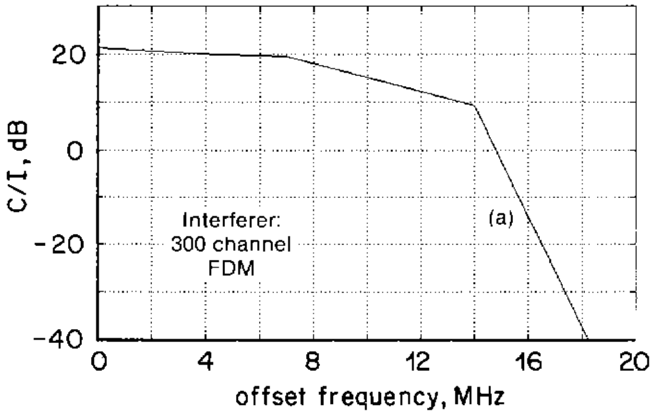


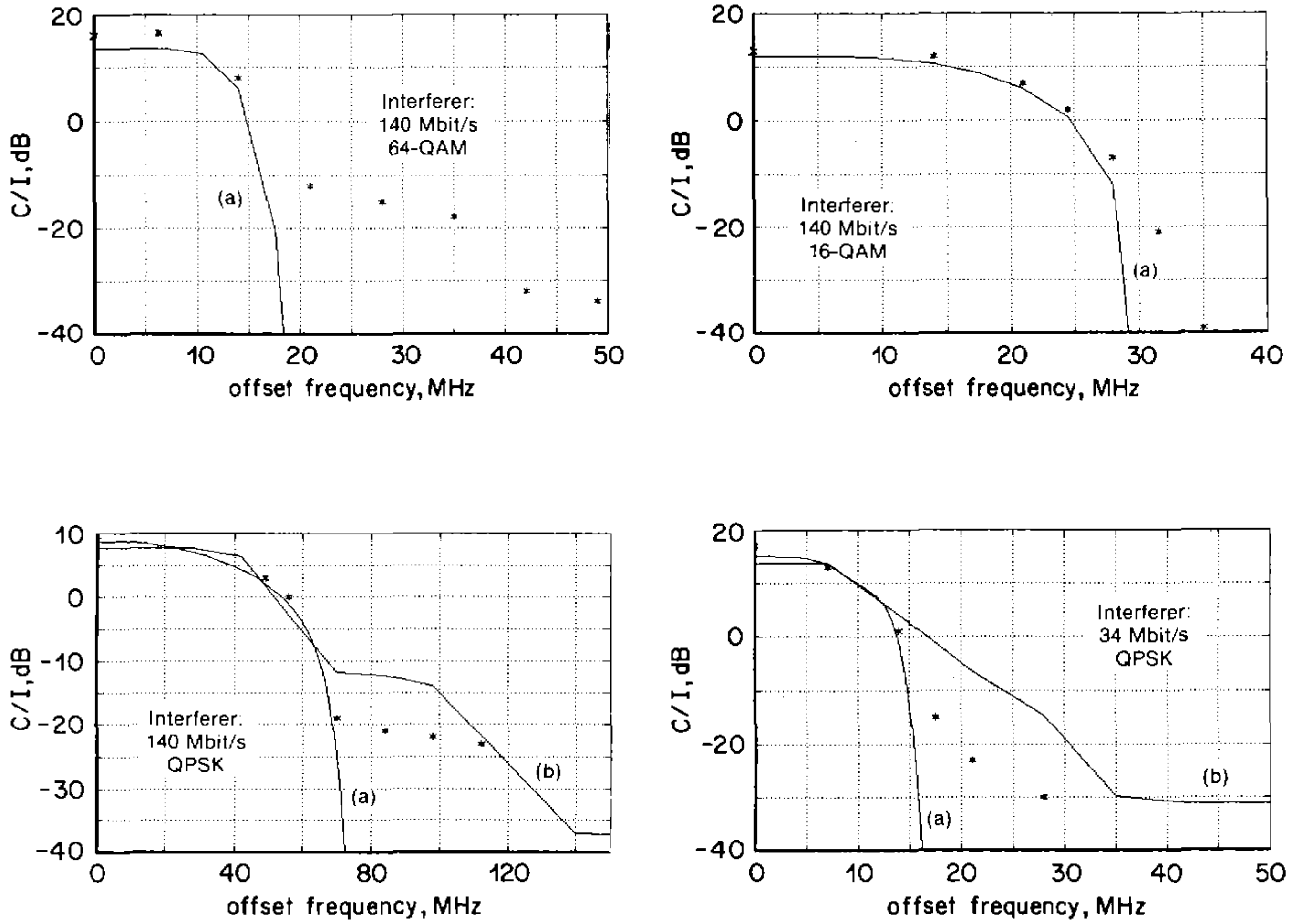
Fig. A4.8 - Calculated and measured results for 34 Mbit/s QPSK as the wanted system and various interfering systems.

1 dB degradation in *C/N* at a BER threshold of 1×10^{-6}.

(a) calculations with theoretical-shaped interfering spectrum (curve tends to infinite isolation at large offset frequencies)

(b) calculations performed using spectrum mask shapes (curve tends to a limiting isolation at large offset frequencies)

Wanted signal: **8 Mbit/s QPSK**



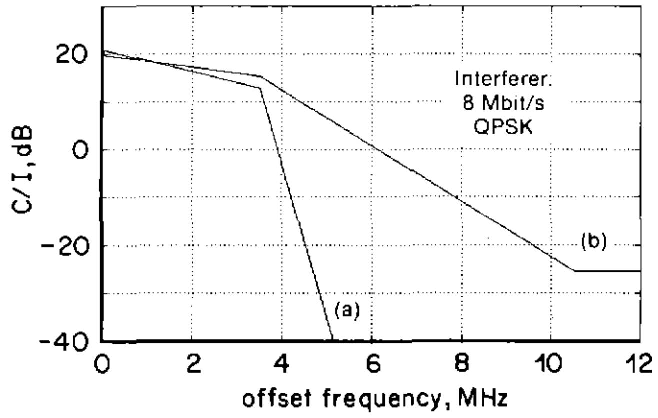
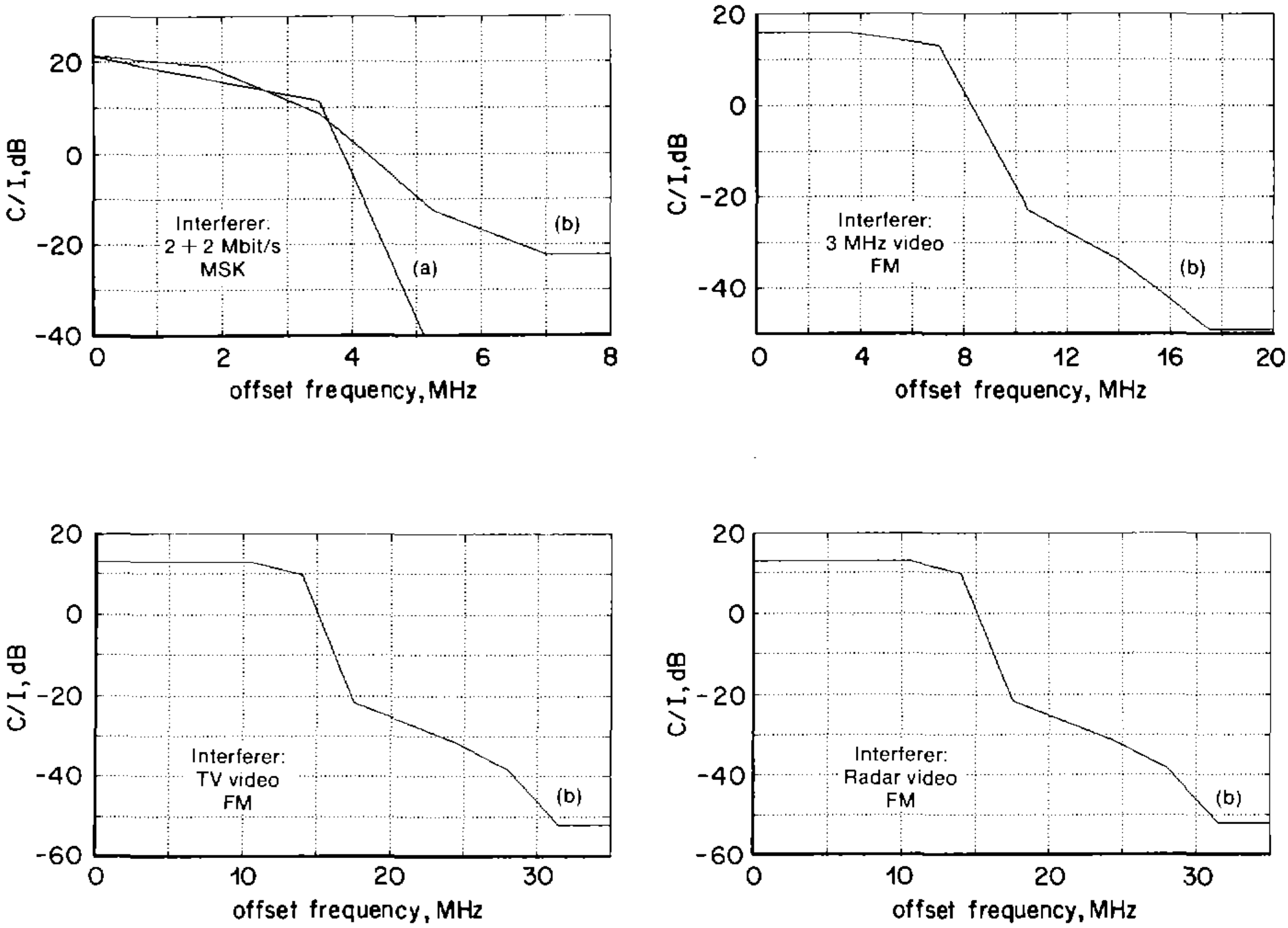


Fig. A4.9 - Calculated and measured results for 8 Mbit/s QPSK as the wanted system and various interfering systems.

1 dB degradation in C/N at a BER threshold of 1 × 10^{-6}.

- * measured points
- (a) calculations with theoretical-shaped interfering spectrum (curve tends to infinite isolation at large offset frequencies)
- (b) calculations performed using spectrum mask shapes (curve tends to a limiting isolation at large offset frequencies)

Wanted signal: **8 Mbit/s QPSK**



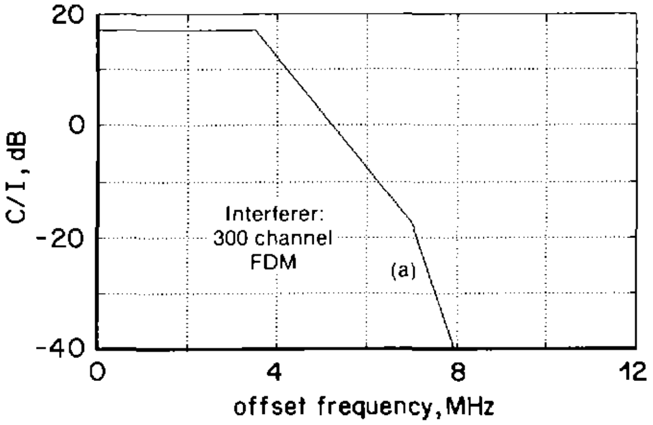
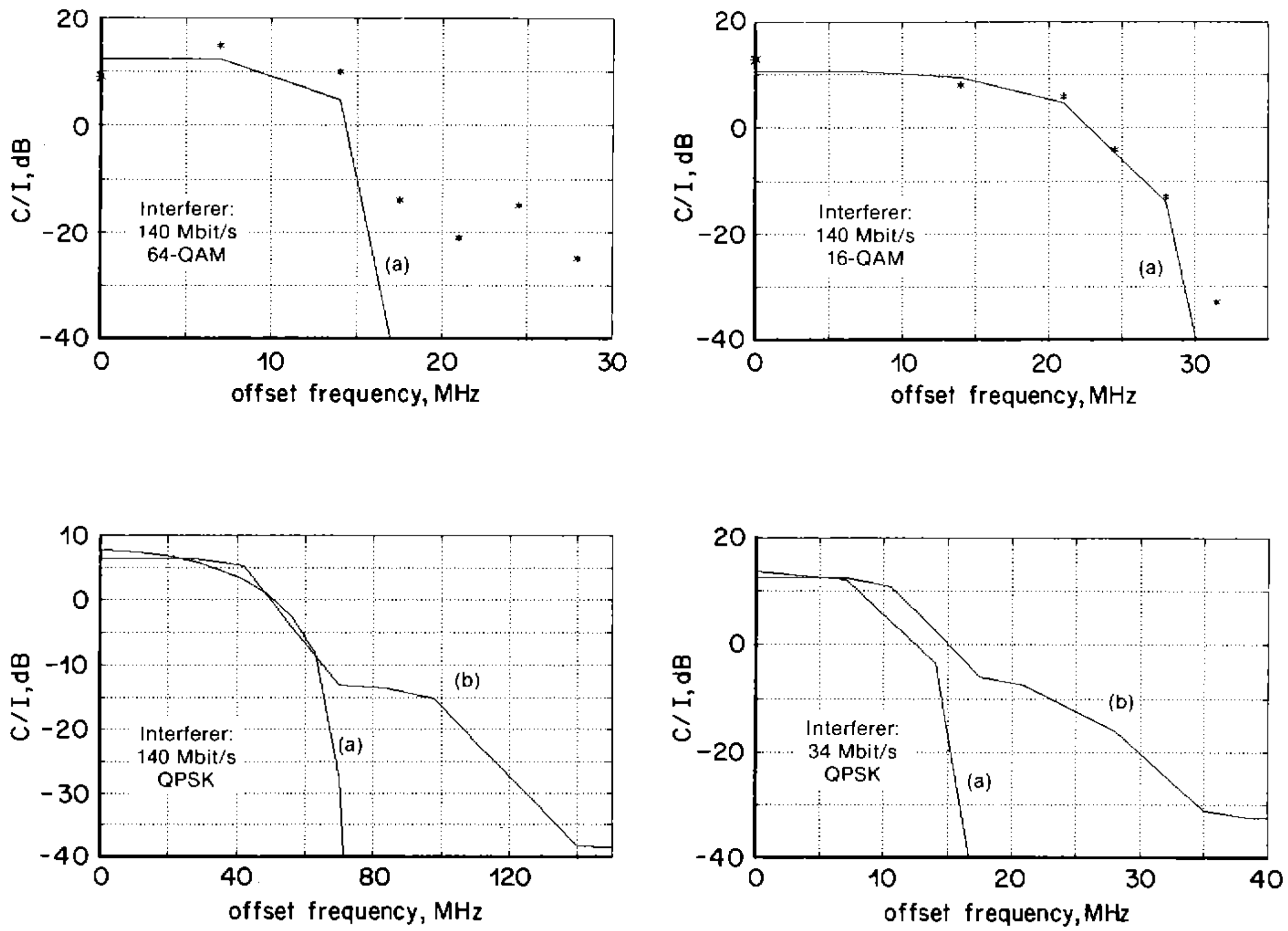


Fig. A4.10 - Calculated and measured results for 8 Mbit/s QPSK as the wanted system and various interfering systems.

1 dB degradation in *C/N* at a BER threshold of 1×10^{-6}.

- (a) *calculations with theoretical-shaped interfering spectrum* (curve tends to infinite isolation at large offset frequencies)
- (b) calculations performed using spectrum mask shapes (curve tends to a limiting isolation at large offset frequencies)

Wanted signal: **2 + 2 Mbit/s MSK**



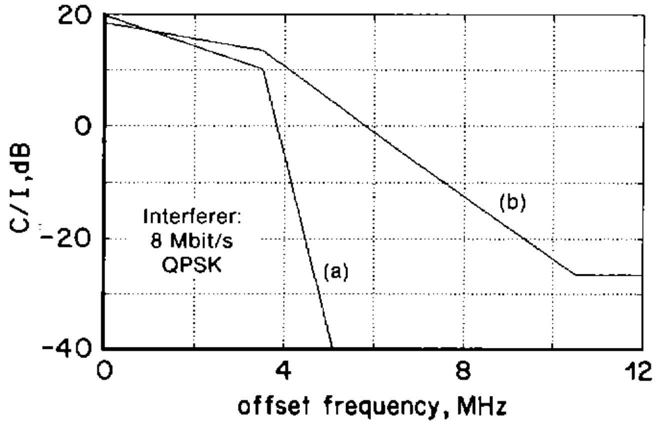


Fig. A4.11 - Calculated and measured results for 2 + 2 Mbit/s MSK as the wanted system and various interfering systems.

1 dB degradation in *C/N* at a BER threshold of 1×10^{-6}

- ∗ measured points
- (a) calculations with theoretical-shaped interfering spectrum (curve tends to infinite isolation at large offset frequencies)
- (b) calculations performed using spectrum mask shapes (curve tends to a limiting isolation at large offset frequencies)

Wanted signal: **2 + 2 Mbit/s MSK**

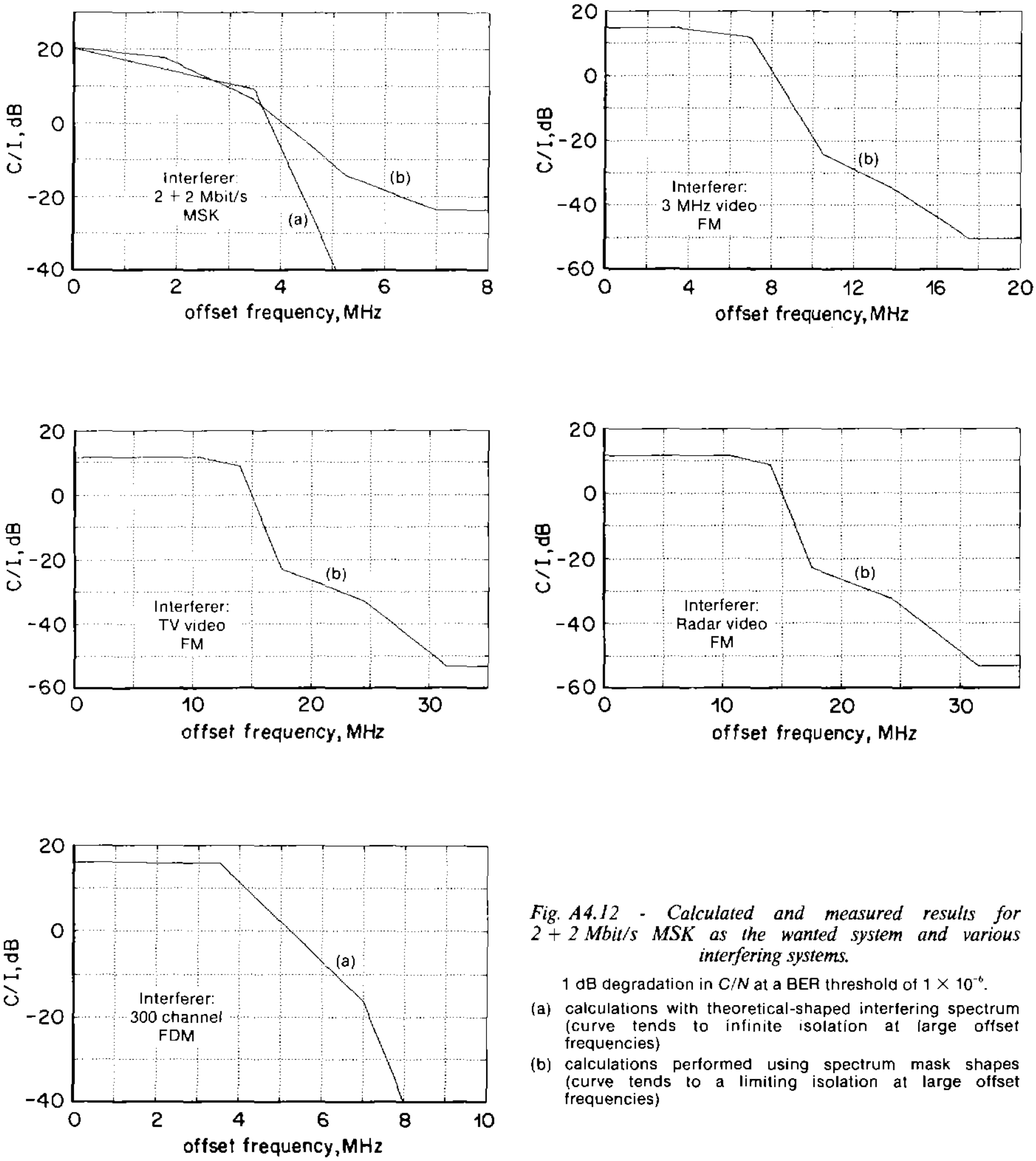
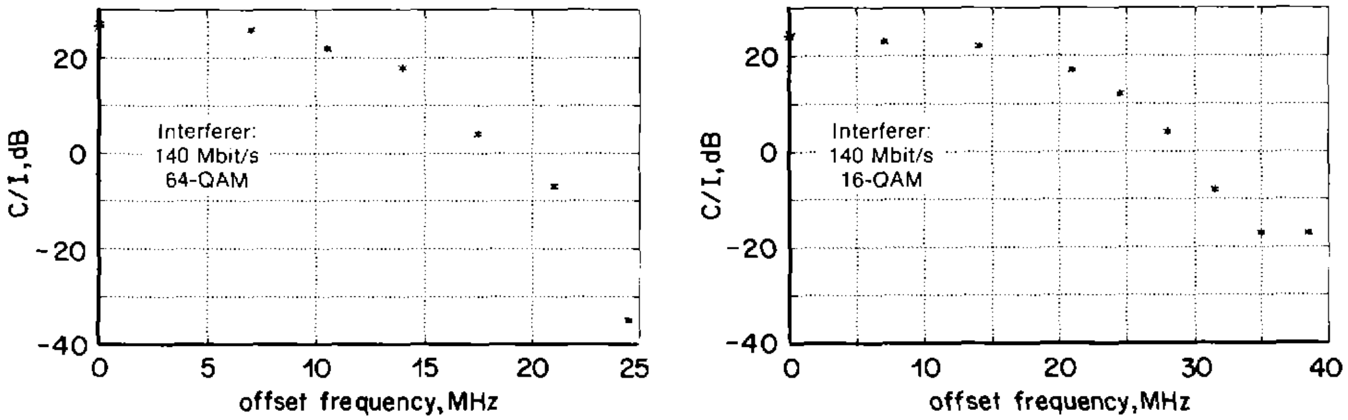


Fig. A4.12 - Calculated and measured results for 2 + 2 Mbit/s MSK as the wanted system and various interfering systems.

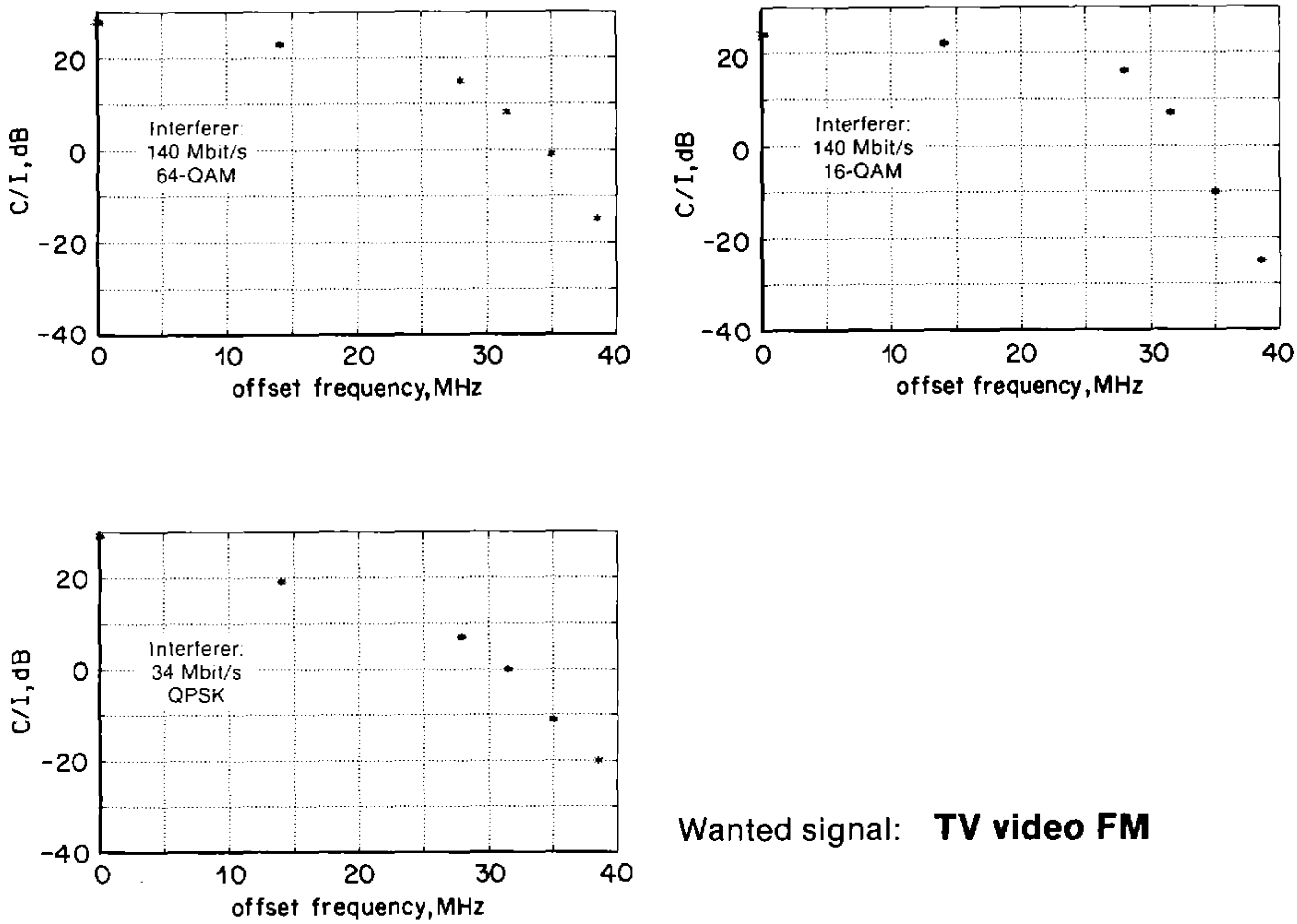
1 dB degradation in C/N at a BER threshold of 1 × 10^{-6}.

(a) calculations with theoretical-shaped interfering spectrum (curve tends to infinite isolation at large offset frequencies)

(b) calculations performed using spectrum mask shapes (curve tends to a limiting isolation at large offset frequencies)



Wanted signal: **3 MHz video FM**



Wanted signal: **TV video FM**

Fig. A4.13 - Calculated and measured results for 3 MHz and TV video as the wanted systems and various interfering systems.

1 dB degradation in *C/N* at a BER threshold of 1 × 10^{-6}.

* measured points

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